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Physics Division Annual Review
1 April 1986–31 March 1987

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PHYSICS DIVISION ANNUAL REVIEW

1 April 1986--31 March 1987

Donald S. Gemmell
Division Director

August 1987

Preceding Annual Reviews

ANL-84-24	1983-1984
ANL-85-22	1984-1985
ANL-86-22	1985-1986

Edited by Karen J. Thayer

FOREWORD

The Physics Division Annual Review presents a broad but necessarily incomplete view of the research activities within the Division for the year ending in March 1987.

At the back of this report a complete list of publications along with the Division roster can be found.

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ATOMIC AND MOLECULAR PHYSICS RESEARCH

NUCLEAR PHYSICS RESEARCH

Introduction

The major portion of the research carried out in the Argonne Physics Division is in nuclear physics making use of a number of experimental and theoretical techniques. Argonne work contributes to most of the frontier areas of the discipline.

The ATLAS facility is the focus of a good portion of experimental research carried out in the Division. ATLAS is a heavy-ion accelerator that pioneered superconducting rf technology. The present system has been in operation for over a year. The beams from ATLAS (up to mass of about 100) are the mainstay of a research program in heavy-ion physics. Energies available are up to several times the height of the Coulomb barrier, a range ideally suited for the exploration of the interface between nuclear structure and dynamics. ATLAS is a national facility with a user group of some 200 scientists from many universities and laboratories.

Some highlights from ATLAS in the past year include the observation of a reaction mechanism similar to the "strongly-damped processes" known at higher energies, but at very low incident energies, below the Coulomb barrier. The study of high spin states and of substantial changes in nuclear structure along and above the yrast line is continuing with the Argonne-Notre Dame BGO facility. And the techniques of accelerator mass spectroscopy have been successfully extended to the observation of ^{41}Ca at the level of concentration that is present in the biosphere. The development of a different class of resonators for a new positive-ion injector for ATLAS is continuing very successfully so that with an ECR source very substantial (several-orders-of-magnitude) increases in beam intensity may be expected by 1989, with a capability for heavier ions, including uranium, following shortly thereafter.

In medium-energy physics experiments were carried out at Bates and at SLAC and major experiments started several years ago entered the data-collection mode: at LAMPF on neutrino oscillations, at FNAL on deep-inelastic muon scattering, and at the BEVALAC on relativistic heavy-ion scattering. Significant progress was made in the development program for a polarized deuteron target.

In nuclear theory work is focussed on the exploration of nuclear forces and subnucleon degrees of freedom, on theoretical understanding of intermediate energy reactions, on variational calculations of finite many-body systems, on exotic (superdeformed and octupole) shapes in nuclei and a number of other topics.

I. MEDIUM-ENERGY PHYSICS RESEARCH

INTRODUCTION

A principal objective of medium-energy research in the Argonne Physics Division is to study subnucleonic processes in nuclei and to determine their role in shaping the character of nuclear forces. To address this issue, the program has emphasized investigations of the excitation of subnucleonic degrees of freedom in nuclear matter -- pion propagation, delta resonance formation, and, more generally, the quark degrees of freedom in the nuclear medium. Pion scattering and absorption have been studied by the Argonne group over the past ten years at LAMPF in a seminal series of experiments. Currently, the electroproduction of the delta in nuclear matter is the subject of an Argonne-led experiment which uses the nuclear physics facility at SLAC. Excitation of the delta is an essential element of the force between nucleons at short range. A notable achievement in 1986 was the construction and installation of a spectrometer detector package and the completion of the data-acquisition phase of that experiment. At much higher energies, Argonne is carrying a major responsibility for managing the on-line data-acquisition software in an experiment to be performed with 600-GeV muons at Fermilab. The data from this experiment, E665, will address a central issue, modification of the structure of the nucleon in nuclear matter. Polarization measurements in electron-deuteron scattering are of major interest because of the insights they may provide on the short-range properties of nuclear forces and the validity of perturbative QCD in the GeV region. Work continues on the development of a polarized deuterium jet target which would be used to perform this experiment in an electron storage ring. In another endeavor, intermediate-energy and relativistic heavy-ion reactions with nuclei are being used to study reaction mechanisms and the nuclear equation of state at very high energy density. The group is participating in an experiment at the Brookhaven AGS which will involve reactions with ions of energies of 15 GeV per nucleon. All of these efforts will provide new data on nuclear forces at short distances or high energy density where the internal excitations of the nucleon are important.

Weak interactions at low energy is the second major area of concentration of the medium-energy physics program in the Argonne Physics Division. Much of our understanding of the fundamental weak interaction has come from low-energy experiments. The program in the Argonne Physics Division is involved in testing the "Standard Model" of unification of weak and electromagnetic forces as well as searching for phenomena that signal physics beyond our present understanding. Argonne is a major collaborator in a neutrino oscillation experiment (E645) in progress at Los Alamos which could provide clues for understanding the nature of neutrino masses and mixings. Measurements of free neutron beta-decay are carried out at the Institute Laue-Langevin in collaboration with scientists from the University of Heidelberg and the ILL. These measurements give the best determination of the ratio of the axial vector-to-vector coupling constant of the neutron. This ratio has profound implications for the weak interaction and for astronomy and astrophysics. Most recently the neutron lifetime was measured directly in order to clarify long-standing inconsistencies among previous experiments. A complementary experiment to obtain a precise value for the vector coupling constant is underway. This experiment may tell us the number of generations of quarks and leptons that exist in nature.

The Argonne group provides the leadership for two experiments in progress with the SLAC NPAS program. To prepare for these measurements Argonne has developed, installed, and is modifying the instrumentation for the 1.6-GeV spectrometer. One of these measurements will provide the first separation of longitudinal and transverse electromagnetic excitations in the delta region in nuclei. While the transverse component of the cross section is essential for a detailed study of the delta, the longitudinal cross-section measurements will provide information on the Coulomb sum rule, an issue raised by recent data from Saclay. The second experiment concerns measurement of the deuteron photodisintegration cross section between 0.8 and 2.0 GeV. These data will be of great interest because they will provide a direct test of the divergent predictions of perturbative QCD and Boson-exchange models for the nucleon-nucleon force. Beam time is scheduled for this experiment in 1987.

At Fermilab, Argonne members are collaborating to bring into operation an experiment (E665) to observe deep-inelastic muon scattering in coincidence with leading hadrons from a variety of nuclei. This experiment will be distinguished from previous efforts by its very high muon energy, 600 GeV, and more detailed particle identification. The primary objectives of the collaboration are the study of the quark hadronization process and the mass dependence of the quark structure functions. The primary responsibility of the Argonne group is to provide leadership in the nuclear physics issues in the experiment and to coordinate the software development for data acquisition.

Two other important initiatives involve electron-scattering experiments. One stems from the need to have a good understanding of the nucleon mean free path in nuclei in order to interpret more quantitatively results of recent pion-absorption studies. The intent of an experiment in progress at the MIT-BATES Laboratory is to provide a much better constraint on the mean-free path by performing (e,e'p) coincidence measurements in the quasifree region for a variety of nuclei. The second involves measurement of the polarization in electron-deuteron elastic scattering, a widely-accepted test of nonnucleonic effects in nuclei, most notably meson-exchange and quark effects. In order to perform this measurement the Argonne group has proposed that a polarized deuterium gas target be located inside an electron storage ring. A prototype polarized deuterium gas jet target has been constructed to test the concept and testing of the system is in progress.

Activities with intermediate and relativistic heavy ions include two major collaborations. One is a study of momentum and energy transfer in nucleus-nucleus collisions in the energy regime 50-100 MeV per nucleon. This energy range is of interest because it lies in a region of transition from nucleus-nucleus interactions to reactions dominated by nucleon-nucleon interactions. The experiment, which was carried out at the BEVALAC, is now in the data-analysis phase. The second, an experiment (E802) at the Brookhaven National Laboratory AGS is concerned with particle-production systematics in reactions induced by 15-GeV-per-nucleon ^{32}S and ^{16}O ions. This experiment will be performed during 1987. Argonne members of the collaboration have responsibility for the design and development of the event trigger.

The search for neutrino oscillations at LAMPF is a major activity of the Argonne weak-interactions group. The experiment (E645) is a collaborative effort with physicists from Cal Tech, Los Alamos, Ohio State, and Louisiana

State University. The cosmic-ray shield for the neutrino detector was built by the Argonne group. First data taken in late 1986 are now being evaluated. In parallel with this activity, Argonne physicists pursue studies of neutron beta decay and beta decay in light nuclei. Noteworthy accomplishments in this area include new measurements of the neutron beta decay asymmetry parameter and of the neutron lifetime. A new measurement, in progress, of the partial decay rate of ^{10}C will further constrain the vector coupling constant which determines the Cabibbo angle.

A. NON-NUCLEONIC EFFECTS IN NUCLEI

Subnucleonic degrees of freedom in nuclear matter, that is the internal structure of the nucleon as it influences the structure of nuclei, is the common theme of the Physics Division medium-energy program. Topics under study include pion propagation, delta formation, and quark dynamics in the nuclear medium. Fermilab experiment E665, the next generation deep-inelastic muon scattering measurement will address a central question in nuclear physics of how nucleon properties are modified in nuclear matter. The Argonne National Laboratory group is managing the data-acquisition software and operating one of the threshold Ĉerenkov detector systems for this experiment. A rigorous test of theories of the short-range properties of nuclear forces and possible QCD effects in nuclei would be a measurement of the polarization in electron-deuteron scattering at high momentum transfer. The Argonne group, in collaboration with members of the atomic physics group, is actively engaged in developing a polarized deuterium jet target which is the essential element of experiments planned in electron storage rings. The Argonne group leads two experiments at the Nuclear Physics Facility at SLAC. One, concerned with the electroproduction of the delta in nuclei, will be the first to provide a separation of the longitudinal and transverse electro-excitation cross section in the delta region for nuclear targets. The second, a study of photodisintegration of the deuteron in the GeV region, will test explicit predictions of perturbative QCD for exclusive reactions involving nuclear targets. Pion and delta propagation are the primary focus of (πNN) experiments in ^{3}He. These measurements provide crucial information on the pion absorption mechanism, including the three-body absorption process. An important question in nuclear physics which arose in the course of the pion absorption studies is the magnitude of the nucleon mean free path in nuclei. The subject is under study in a quasifree electron scattering experiment which will be completed at the MIT-BATES Laboratory in 1987. The first studies of electoproduction of pions in nuclei will begin in 1987 with a collaboration at the ALS-Saclay accelerator involving members of the Argonne and Saclay staffs.

a. **Deep-Inelastic Muon Scattering from Nuclei with Hadron Detection**

(D. F. Geesaman, R. Gilman, M. C. Green, H. E. Jackson, S. Kaufman, M. Adams,** J. F. Bartlett,‖ H. Braun,¶¶ T. H. Burnett,§§ A. Eskreys,‡ W. R. Francis,* J. Haas,§ C. Halliwell,** V. Hughes,*** T. B. W. Kirk,‖ V. Kistiakowsky,‡‡ H. G. E. Kobrak,* S. Krzywdzinski,§§ S. Kunori,†† J. J. Lord,§§ H. J. Lubatti,§§ P. Malecki,‡ A. Manz,‖‖ S. McHugh,* D. McLeod,** H. Melanson,‖ W. Mohr,§ H. Montgomery,‖ J. Morfin,‖ R. Nickerson,¶ L. Osborne,‡‡ A. M. Osborne,† F. M. Pipkin,¶ R. Raja,‖ N. Schmitz,‖‖ P. Schuler,*** J. Seyerlein,‖‖ A. Skuja,†† G. Snow,†† P. Steinberg,†† H. E. Stier,§ R. W. Swanson,* H. J. Trost,‖‖ J. Wilkes,§§ R. Wilson,¶ S. Wolbers,‖ and G. Wolf,‖‖)

Deep-inelastic muon scattering from nuclei provided the first convincing evidence that the structure of nucleons is modified in the nuclear medium. This has profound implications on the understanding of nuclear dynamics. Many low-energy nuclear measurements have previously suggested interpretations involving modification of the nucleon structure. However the muon-scattering data which are sensitive to the incoherent scattering from the quarks in nuclei can indicate the difference between the quark distribution functions in the free nucleon and in nuclei. The conclusion of these studies was that the distribution of the fraction of the momentum carried by the quarks, $F(x)$, is shifted to lower fractional momenta, x. Theoretical interpretations include a possible rescaling of the nucleon size in nuclear matter or the effect of an enhanced meson field in the nuclear interior.

A new experiment, E665, using the Tevatron II at Fermi National Accelerator Laboratory will provide new information on the nuclear effects on nucleon properties by studying deep-inelastic muon scattering with coincident hadron detection. The key features of this experiment are: 1) an open

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geometry allowing essentially 4π-hadron detection. 2) A streamer chamber vertex detector for low-energy fragments. 3) Two large-field-volume superconducting magnets, with field strengths of 4 T-m and 7 T-m to provide accurate measurements of the muon and hadron momenta. 4) A particle identification system including a ring-imaging Čerenkov counter which can separate pions, kaons and protons from 7.0 GeV/c to 150 GeV/c. 5) A muon beam energy of 600 to 800 GeV, a factor of two higher than was previously available. This high beam energy makes the experiment particularly suited to the study of the region of $x < 0.1$, where there is little or no data from other measurements. The complete spectrometer system is shown in Fig. I-1.

The hadron detection provides several important new directions for this research. With the excellent particle identification, the flavor dependence of the fragmentation properties of nucleons in nuclei can be studied. This allows the isolation of features of the quark sea from the valence quark distributions. Furthermore, the time required for the struck quarks to form hadrons is sufficiently long that hadronization takes place both inside and outside the nucleus. This permits the study of the propagation of quarks through the nucleus and the effects of the nucleus on the hadronization process.

Argonne is responsible for two aspects of the experiment. The first is the management of the on-line software. Recent Argonne efforts have concentrated on testing the system concepts, developing scaler and message facilities and implementing monitoring strategies and techniques. The most serious issues involve the flow of data and control information between the various machines. Data are read in through three front-end PDP 11/34's via CAMAC and FASTBUS. These front ends are linked to a micro-VAX 11 for data concatenation and tape logging. Online analysis is performed by sampling events on a VAX 11/780. The data-acquisition software is based on the FNAL DA and VAX-ONLINE systems developed at Fermilab.

Argonne is also responsible for a gas-threshold Čerenkov counter, C1 which is required for particle identification in the 1-20-GeV/c region. During 1986, the counter was installed in place in the experiment and it was verified that the magnetic environment between the two magnets was acceptable for operation. Work is beginning on integrated particle-identification strategies for the experiment.

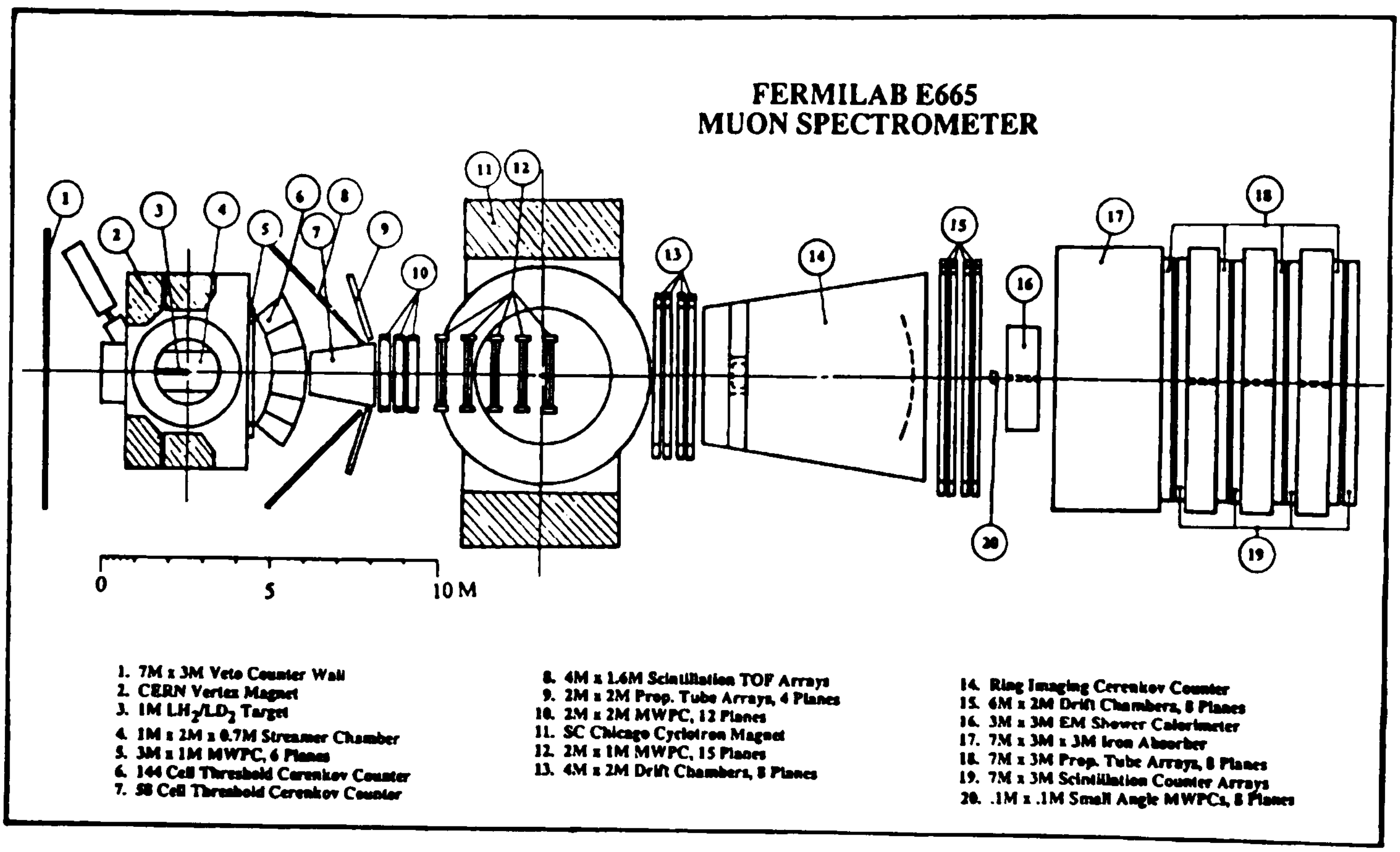

Fig. I-1. Particle spectrometer and identification system for Fermilab experiment E665, a study of deep-inelastic muon scattering at 600-700 GeV.

During the summer of 1985, the muon beam line was commissioned and the first beam present in the new experimental hall was used for detector tests. Roughly 70% of the experimental equipment was in place at this time. During 1986 most of the rest of the experimental equipment was brought into operation.

The experiment is scheduled for 5 months of beam time beginning in June 1987 with a second five-month period in 1988. Measurements are planned on targets of hydrogen, deuterium, argon and xenon.

b. **Electron-Deuteron Scattering with a Polarized Deuterium Gas Target in an Electron Storage Ring** (R. J. Holt, D. F. Geesaman, M. C. Green, R. Kowalczyk, L. Young, B. Zeidman, and B. Norum*)

It is expected that the most powerful method of isolating the charge and quadrupole form factor of the deuteron involves electron elastic scattering from a tensor-polarized gas target in an electron storage ring. It is estimated that high-accuracy measurements of polarization in electron-deuteron scattering could be performed up to a momentum transfer of $q^2 = 20$ fm^{-2} at the Aladdin elctron storage ring at Stoughton and up to ~40 fm^{-2} at the PEP storage ring at SLAC.

As a feasibility study of this method we have been testing a novel scheme for producing a high flux of polarized deuterium atoms at the ANL Dynamitron facility. This method is based upon spin-exchange optical pumping, and consequently, the two key advantages of this method over conventional polarized sources are: (i) the flux from the source is expected to be limited only by laser power and (ii) low-background gas load to the storage ring.

During the past year much progress has been made in the testing of a prototype source. In particular, we have found for the first time, a signal for polarized deuterium in the spin-exchange cell. This observation was based on the use of a Zeeman transition method shown schematically in the upper half of Fig. I-2. The flourescent light from the optical pumping of K when the RF coil is swept through the Zeeman transition frequency for deuterium is shown in the lower half of the figure.

*University of Virginia, Charlottesville, VA.

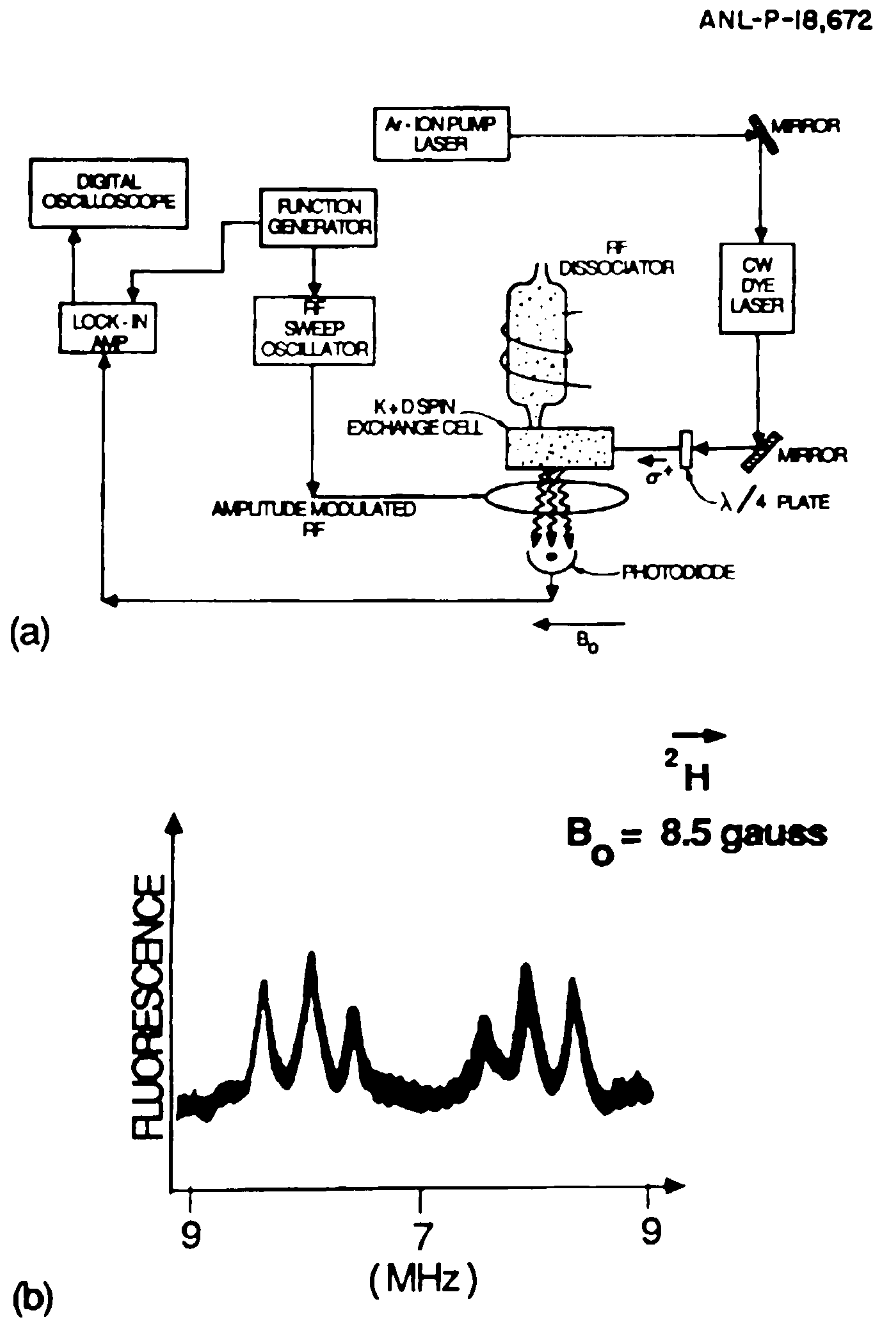

Fig. I-2. A schematic diagram of the apparatus to observe Zeeman transitions in the spin-exchange cell is shown in the upper half. The fluorescence from K for the Zeeman transitions in D are shown in the lower half of the figure. Two patterns appear since the RF oscillator was set to sweep both upward and downward in frequency in order to help eliminate any false asymmetries.

Of course, this signal would not be present for a vanishingly-small deuterium polarization since the Zeeman levels would be equally populated. A simple analysis based upon spin-temperature considerations yields a polarization P_z of 5% for deuterium with a flux of approximately 1×10^{17}.

At present, the immediate plan is to optimize the polarization of the source and increase the flux by boosting the laser power to ~500 mW. The goal is to achieve a t_{20} of $\gtrsim 0.3$ and a flux of $\gtrsim 2 \times 10^{17}$ atoms/s before constructing an internal target for a storage ring. The polarization will be measured finally with the use of the ^{3}He beam from the ANL Dynamitron.

c. **Two-Body Photodisintegration of the Deuteron in the GeV Region**
(R. J. Holt, S. Freedman, D. F. Geesaman, R. Gilman, M. C. Green, H. E. Jackson, T.-S. H. Lee, N. Napolitano, B. Zeidman, T. Y. Tung,* R. E. Segel, D. Baran,* P. Bosted,† J. Jourdan,‡ B. Filippone,‡ R. McKeown,‡ R. Minehart,§ Z. E. Meziani,¶ and B. Mecking‖

At present there exist no data for two-body photodisintegration of the deuteron above a photon energy of 1 GeV. The primary interest in extending the experiments to high energy is to perform measurements of this simplest nuclear process where subnucleonic processes dominate the cross section. For example, a recent meson-exchange calculation performed at Argonne indicates the cross section for this reaction should be substantially larger than that predicted by perturbative QCD. Our intention is to perform the measurements up to a photon energy of 1.8 GeV at the NPAS (Nuclear Physics at SLAC) facility.

In order to perform this experiment, the collaboration is modifying the 1.6-GeV spectrometer to detect protons from the D(γ,p)n reaction. The new detector package for the spectrometer is shown schematically in Fig. I-3. In particular, a high-resolution time-of-flight system and an aerogel Čerenkov detector are being developed for the experiment. It is expected that this experiment will begin at SLAC during 1987.

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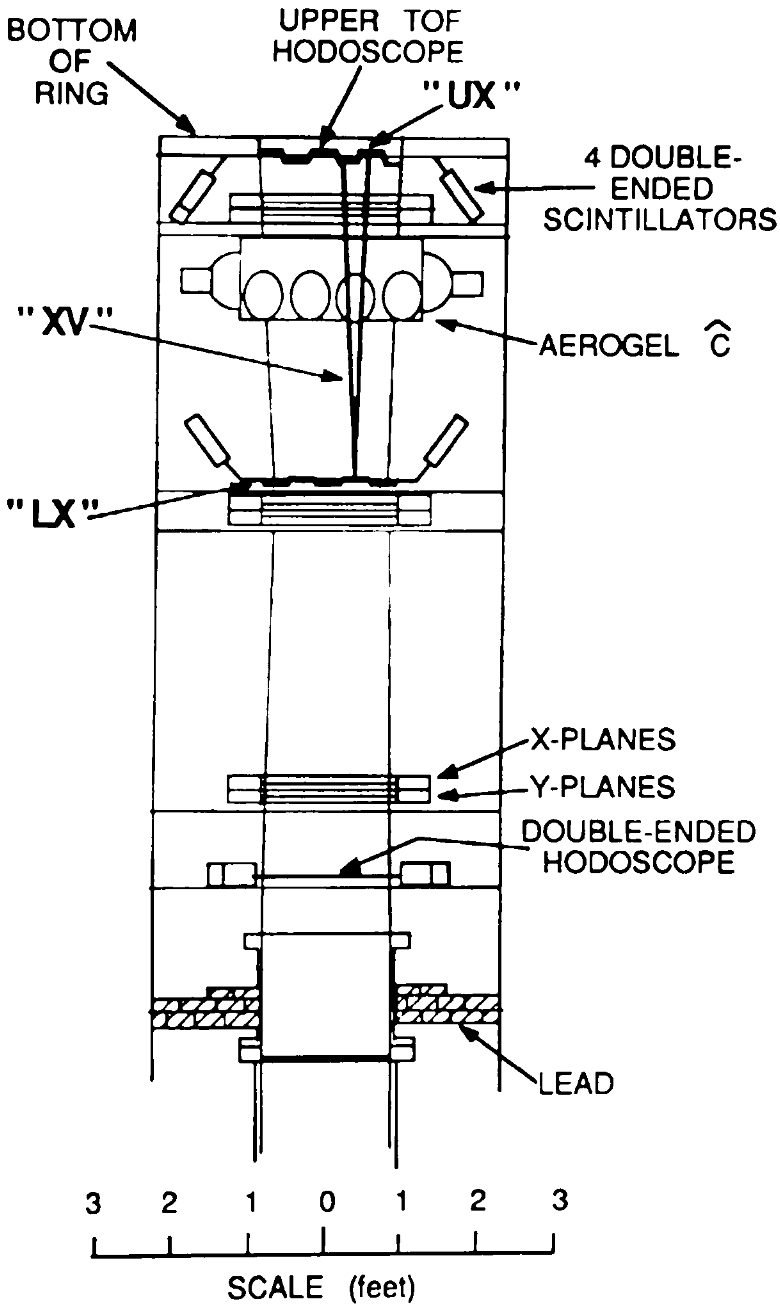

Fig. I-3. Schematic diagram of the hadron detector system in the 1.6-GeV spectrometer for the D(γ,p)n experiment. The aerogel Cerenkov detector and the high-resolution time-of-flight system will be employed to distinguish protons from pions or positrons.

d. **Tensor-Polarized Deuterium Target Performance Modeling** (M.C. Green)

In support of the tensor-polarized deuterium target development project, a number of computer programs have been developed in relation to the prototype polarization system now under experimental study. These programs include 1) a spreadsheet program to predict the molecular flow characteristics of the system given polarization cell dimensions, deuterium flow rates and potassium vapor temperatures; 2) a SPEAKEZ program, ENGLISH, which solves nonlinearly-coupled rate equations to predict the deuterium polarization in the prototype cell; and 3) a set of SPEAKEZ programs which use ENGLISH to generate families of performance curves for various experimental conditions. Most recently, selective RF depolarization of the deuterium is being experimentally developed as a diagnostic for optimizing deuterium polarization. A SPEAKEZ program RABI has been developed to predict the appropriate RF frequencies to accomplish depolarization. The program ENGLISH has also been modified to predict the system response to selective RF depolarization. Future software modeling efforts will be directed towards 1) design studies of a full-scale target for use in an electron storage ring, 2) enhancements to ENGLISH to include effects of imperfect circular polarization of the laser light, and 3) the development of a Monte Carlo program to predict target performance for high deuterium flows.

e. **Electroproduction of the Delta Isobar in Nuclei**
(D. Baran,* D. Geesaman, M. Green, R. Holt, H. Jackson, B. Zeidman, P. Seidl, B. Filippone,† J. Jourdan,† R. McKeown,† R. Milner,† D. Pottervelt,† R. Walker,† R. Segel,‡ and J. Morgenstern§)

The electroproduction of the delta isobar in complex nuclei is under study in an experiment which is part of the Nuclear-Physics-at-SLAC (NPAS) program. The 1.6-GeV and the 8-GeV spectrometers have been used to investigate the scattering of medium-energy (T = 0.5 to 2.0 GeV) electrons by targets of ^{12}C and ^{56}Fe. The particular feature to be studied in this experiment will be the separation of the longitudinal and transverse cross

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sections at relatively low four-momentum transfer, $Q^2 = 0.1\ (GeV)^2$, where the kinematic conditions correspond to those obtained in pion excitation of the delta. Since the excitation of the (3,3) resonance is the dominant feature of both pion and electron interactions at medium energies, an understanding of the nuclear response function requires a detailed knowledge of delta propagation in nuclei. Inasmuch as there are distortions and strong absorption present in pion-induced excitation of the delta, electroproduction is the only way to produce delta-hole excitations uniformly throughout the nucleus and to investigate delta isobar dynamics in the nuclear medium. In preliminary analysis of data for C and Fe, the cross sections per nucleon in the delta region are equal. Radiative corrections are small at the higher incident energies. The cross sections per nucleon after radiative corrections for C and Fe are shown in Fig. I-4.

f. **Pion Electroproduction in Deuterium** (H. E. Jackson, R. Gilman, R. Holt M. Bernheim,* G. Fournier,* A. Gerárd,* J. Julien,* J. M. Laget,* A. Magnon,* C. Marchand,* J. Morgenstern,* J. Mougey,* J. Picard,* D. Reffay,* B. Saghai,* S. Turck-Chieze,* and P. Vernin*)

Pion electroproduction on nucleons bound in nuclear matter may be significantly different from production on free nucleons because of the contributions of higher-order processes involving neighboring nucleons. Such multinucleon processes are a basic feature of nuclear matter and their study can provide useful insights into the properties of nuclear forces. To explore the use of electroproduction as a probe of such processes we have begun a series of experiments at the Saclay electron linac (ALS) to study the reaction in simple nuclear systems. The deuteron has been chosen for the first measurement because it is a simple benchmark nucleus for which theoretical calculations can be made. The Saclay high-energy, high-resolution coincidence spectrometer (HE3), will be used to observe pions emitted in the direction of the virtual photon in coincidence with the scattered electron. Measurements scheduled for the summer of 1987 will be made for two values of the nucleon invariant mass. The first will be in the region of the peak of the delta (1232 MeV). The second will be for an invariant mass near 1160 MeV. In this

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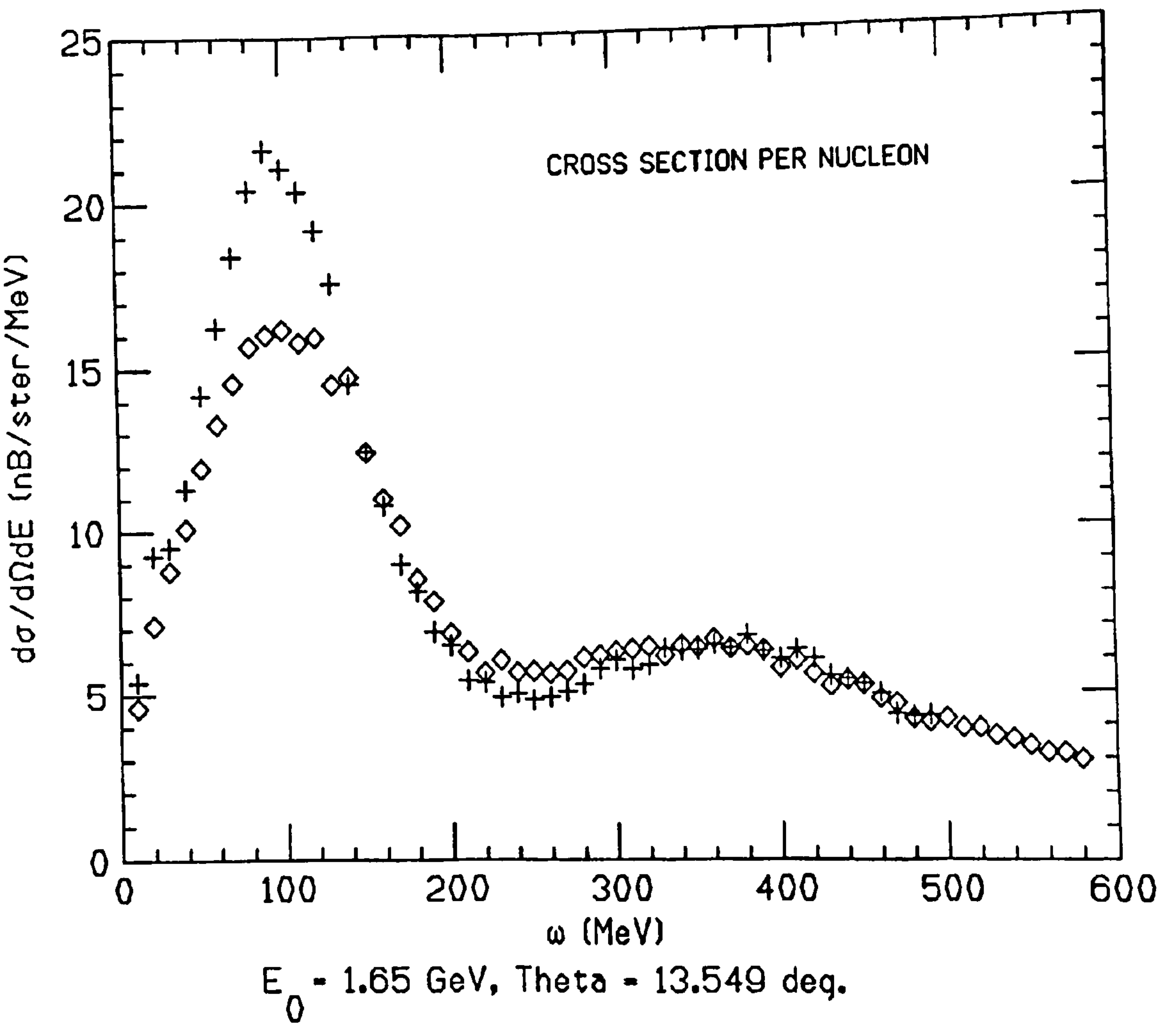

Fig. I-4. Inclusive scattering cross sections per nucleon for 1650-MeV electrons incident on targets of carbon (shown in crosses) and iron (shown in diamonds).

region electroproduction on the proton is predominately longitudinal and the "photo-electric" or pion-pole term provides the largest contribution to the cross section. If there are significant deviations in total yields from the free nucleon values, the shape of the energy spectrum of the pions may provide clues as to their origin. Measurements will be made using deuterium and hydrogen in a single cryogenic target with identical spectrometer geometry. Thus, a direct comparison will be possible without the systematic errors common in absolute measurements.

g. **Study of Pion Absorption in ^{3}He through the (π^+,2p) and (π^-,pn) Reactions** (D. F. Geesaman, J. P. Schiffer, B. Zeidman, D. Ashery,* G. S. F. Stephans,† B. D. Anderson,‡ R. Madey,‡ R. C. Minehart,§ S. Mukhapadhyay,|| E. Piazetsky,¶ R. E. Segel,** C. Smith,§ and J. Watson‡)

The analysis of experimental data from pion absorption at 165-, 250- and 500-MeV pion kinetic energies by ^{3}He is the subject of two Ph.D. theses by students at the University of Virginia and Northwestern University. Progress has been somewhat slower than might have been hoped but contributions to conferences are being prepared now. The most surprising result is that at the higher energies the angular distribution of the coincident proton-neutron pair from π^- absorption appears to be very similar to that at lower energies with the asymmetry having the same sign. Since the data now span energies from below to above the delta resonance, the essentially constant asymmetry suggests that this process does not have an amplitude that proceeds though the delta resonance.

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¶Los Alamos National Laboratory, Los Alamos, NM.
**Northwestern University, Evanston, IL.

h. **The A-Dependence of the (e,e'p) Reaction in the Quasifree Region**

(D. F. Geesaman, M. C. Green, R. J. Holt, J. P. Schiffer, B. Zeidman, T. Tung,* G. Garino,* M. Saber,* R. E. Segel,* E. J. Beise,† G. Dodson,† R. P. Redwine,† W. W. Sapp,† S. A. Wood,† C. F. Williamson,† N. S. Chant,‡ P. G. Roos,‡ J. D. Silk,‡ M. W. Deady,§ and X. K. Maruyama‖)

Information on the propagation of nucleons in the nuclear medium is essential for tests on the nuclear many-body problem and for the analysis of many processes, including pion absorption and inclusive proton scattering. In many instances, proton scattering of a few degrees and energy loss of several MeV is not relevant to the analysis of the fundamental process. Experiment 83-17 is designed to study this macroscopic attenuation of 170 ± 30 MeV protons in the nucleus by studying the A-dependence of the (e,e'p) reaction.

Electron-proton coincidences were measured on targets of carbon, aluminum, ^{58}Ni and tantalum with a 780-MeV electron beam from the MIT-BATES accelerator. Electrons in the energy range of 540-590 MeV were detected in the OHIPS spectrometer at 49.8° in coincidence with protons inthe BIGBITE spectrometer in the energy range of 120-210 MeV and proton angles of 49.3° and 65.1°. The 49.3° proton angle corresponds to the angle for free scattering of an electron with an average three-momentum transfer of 600 MeV/c. Electron singles data were accumulated simultaneously with the coincidence data to provide an independent relative normalization.

Analysis of the experiment is underway. With 2-μA electron currents and 0.8% duty factor, the real-to-random rate was better than 6 to 1. With data at only two angles, it was not possible to cover the entire recoil momentum range. DWIA calculations are in progress for each system. A final run is expected in 1987 to complete the experiment.

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i. **Study of Correlations Between Light Nuclear Fragments and the Scattered Projectile with 300-MeV Protons** (S. B. Kaufman, B. D. Wilkins, R. G. Korteling,* R. E. L. Green,* J. M. D'Auria,* R. L. Helmer,† and K. P. Jackson†)

The emission of light fragments (A < = 4) in coincidence with an energetic proton observed at forward angles (presumably the scattered projectile) has been studied using 300-MeV protons and targets of Be and Ag in an experiment at the TRIUMF Cyclotron. The objective is to place constraints on the different models which have been suggested to account for the inclusive spectra of these fragments, and in particular to distinguish between the contributions of a single-scattering mechanism and a thermal, statistical type process. Although the inclusive spectra of ^3He and ^4He from the two targets are rather similar (except for the Coulomb cutoff for Ag), the coincident spectra are quite different, illustrating the danger of drawing conclusions about reaction mechanisms from inclusive measurements. A strong direct component is seen for the Be target, with both ^3He and ^4He spectra showing enhancements in kinematic regions close to that of the quasifree knockout process. There is no similar enhancement for the Ag target, but an increased ratio of coincidence-to-singles cross sections is observed at or near the correlation angle between the fragment and the scattered proton corresponding to the minimum momentum transfer to the remainder of the nucleus (the so-called Quasi-Two-Body-Scaling angle).

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j. **Focal-Plane Detector for 1.6-GeV Spectrometer at SLAC** (R. Gilman, M. C. Green, R. J. Holt, H. E. Jackson, R. S. Kowalczyk, J. Napolitano, P. Seidl, B. Zeidman, and D. Baran,*)

The focal-plane detector assembly for the 1.6-GeV Spectrometer at SLAC operated in a satisfactory fashion for Experiment NE-1. This general-purpose system consisted of a pair of x-y hodoscopes, three sections of double x-y drift chambers, a gas Čerenkov counter and a shower counter. Data acquisition utilizes ECL logic extensively, thereby permitting individual wire readout of the chambers for high-count-rate capability. For Experiment NE-8, proton detection in the presence of many pions is the problem. For this

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purpose the assembly is being modified as follows: 1) The gas Čerenkov counter is replaced by an aerogel Čerenkov counter for particles with $\beta >$ 0.95. 2) The shower counter is removed. 3) Another hodoscope is being added for time-of-flight measurements. 4) The drift chambers are being modified to generate left-right signals by detection of induced charge on the "field wires". The modified assembly is expected to be completed in the spring of 1987.

k. **Data-Acquisition System for NPAS NE-8** (M. C. Green, P. Bosted,* R. Minehart†)

The data-acquisition system for the upcoming experiment NE-8 at SLAC will be based on the standard acquisition software used in conjunction with all End-Station A experiments. This software is being supplemented by programs and subroutines specific to the operation of the 1.6-GeV spectrometer which were developed for NE-1/5 data-acquisition system (MUPDAS). Software which has or will be converted over to the new system includes code 1) to control ECL discriminators, delay and logic boxes, 2) to calibrate the wire-chamber TDC's, 3) to determine wire-chamber timing offsets, 4) to replay NE-1/5 tape for tracking code development, and 5) to transform input-wire-chamber TDC data providing statistics for chamber performance and input data to tracking routines. In addition, a utility for the terminal display of experimental scaler values is being implemented (SCALEZ) which is a slightly-modified version of the utility SCALE developed for the Fermilab experiment E-665.

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ℓ. **SCALE - A VAX/VMS-Based Terminal-Scaler Display Utility** (M. C. Green)

In support of the Fermilab experiment E-665, a software utility, SCALE has been developed (installed and documented) which displays real-time parameter values (scalers) on a typical computer terminal CRT according to a user-defined format. This utility separates the functions of updating scaler values from that of actually displaying these values into two independent processes. This separation allows for the multiple displays to contain the same scaler value in different formats and for these displays to be changed "on line" without disturbing the updating process. Indeed, which scaler values, formats and labels are displayed are determined from a configuration file which the user can easily create and edit. To assure that all scaler values on a given display come from a specific time epoch, a scaler-value locking capability was implemented. Thus, when the scaler updating process is actively changing the scaler values, the display process is locked out from reading these values for display. And conversely, upon completion of the scaler update, the display process may lock out further updates until it has read all values needed for display. This utility was designed to work in a multiple-experimental-group setting, providing an independent display set capability for each group. Recognizing that some experimental parameters are of interest to all groups, a capability was included for the local scaler displays to reference and display these global parameters ("system scalers"). As part of the SCALE utility, a system-level process was developed to update system scaler values based on input data. This scaler-display utility is written in FORTRAN using VAX system services to generate global sections along with the VAX display software, SMG. As such, SCALE can be easily integrated into almost any data-acquisition system to provide an enhanced scaler display capability.

B. INTERMEDIATE AND RELATIVISTIC HEAVY-ION PHYSICS

The aim of this program is to characterize the interaction between heavy ions and complex nuclei, and to study how the particle-particle interactions are affected by the nuclear medium. The energy region between 40-200 MeV/A constitutes a transition regime and has hitherto not been well studied. At the lower energies the interactions can be described in terms of nucleus-nucleus potential and collective variables for the system. At the higher energies nucleon-nucleon interactions dominate and the central collisions eventually lead to multifragmentation.

Aspects of the problem in the transition regime are addressed in an experiment at the low-energy beamline at the BEVALAC. The question of momentum and energy deposition in the composite system is studied, and the measurements should provide information on the limits to compound-like nucleus formation.

The interactions between heavy ions at relativistic energies are dominated by nucleon-nucleon interactions but the presence of the large number of nucleons in the heavy-ion reactions will give rise to collective effects in the excitation of the intermediate nucleon system. In the energy regime of 5-100 GeV/A (fixed target) the nuclear system will be highly compressed and achieve a large baryon density, while at even higher energies (available at RHIC) the central region is expected to be baryon poor.

The studies at the Brookhaven National Laboratory AGS are aimed at the study of global properties in relativistic heavy-ion collisions under the condition of high nuclear densities. Among the goals are a study of the effective temperature, extension of, and the energy density of the intermediate nuclear system. This is achieved by studying inclusive spectra of emitted particles and two-particle correlations.

a. **Fission and Charged-Particle Emission in Nucleus-Nucleus Collisions at Intermediate Energy** (F. Videbaek, S. B. Kaufman, B. K. Dichter, O. Hansen,* M. J. LeVine,* C. E. Thorn,* A. Pfoh,* W. Trautman,† R. L. Ferguson,‡ H. C. Britt,§ A. Gavron,§ B. Jacak,§ J. Wilhelmy,§ J. Boissevain,§ M. Fowler,§ G. Mamane,‖ and Z. Fraenkel‖)

The momentum and energy transfer in nucleus-nucleus collisions at intermediate energies (50-100 MeV/A) is being studied using heavy-ion beams at the Lawrence Berkeley Laboratory BEVALAC. The objective is to investigate the transition from the low-energy regime describable in terms of potentials and macroscopic variables and the high-energy regime dominated by nucleon-nucleon interactions. The experimental technique is to detect coincident medium-mass fragments using gas detectors capable of energy, mass (via time-of-flight) and position measurements, in coincidence with energetic light charged particles detected with plastic scintillator phoswich telescopes. The momentum transfer can be inferred from the folding angle between the heavy fragments, and the energy transfer from both the fragment kinetic energies and the multiplicity and energies of the light particles. Data were obtained in December 1985, for the system 100-MeV/A ^{56}Fe + ^{197}Au, and are now being analyzed.

The mass correlation of coincident fragments is a strong function of angle, as shown in Fig. I-5. When both fragments are emitted at backward angles on opposite sides of the beam, only events with two light fragments are observed. At a correlation angle of 180°, a prominent group of events is seen in which both fragments have masses close to one-half that of the target; these are due to fission of a target-like residue with little forward momentum, probably following a peripheral collision. The associated charged-particle multiplicity is smaller for these events than for the low-mass events, supporting this conclusion. At more forward angles this fission peak disappears, and a broad distribution of fragment masses is observed. Events in which both fragments are detected on the same side of the beam are also observed at low masses, indicative of large missing momentum. These low-mass events are interpreted as arising in a multifragmentation process in which one or more of the fragments are not detected, for which no strong angular correlation between the two fragments observed is expected.

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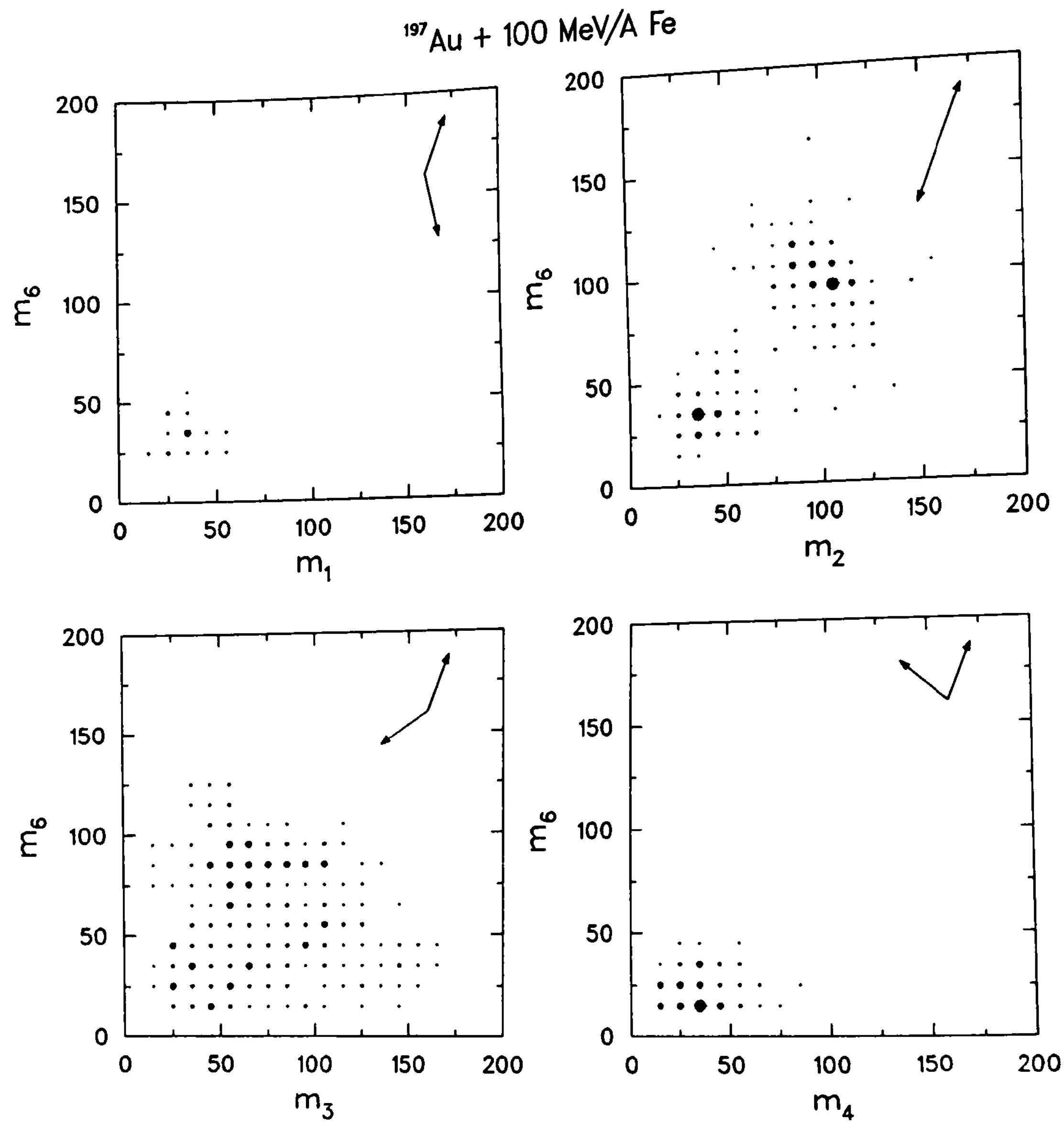

Figure I-5. Correlation between coincident fragment masses for four different angles in reactions of 100-MeV/A Fe with Au. The mean detector angles are indicated by arrows on each plot.

Future plans are to add a set of forward-particle telescopes to detect projectile fragmentation, and to improve the detection efficiency of the gas detectors for lighter fragments. We will propose further measurements with heavy-ion beams of different masses and energies in order to explore the systematics of multifragmentation and its dependence on mass and energy of the projectile.

b. <u>Studies of Particle Production at Extreme Baryon Densities in Nuclear Collisions Produced with ^{16}O and ^{32}S Beams at AGS (E802 Collaboration)</u>

(R. R. Betts, S. B. Kaufman, F. Videbaek, D. Alburger,* D. Beavis,* P. D. Bond,* C. Chasman,* Y. Y. Chu,* J. B. Cumming,* R. Debbe,* E. Duek,* Ole Hansen,* P. Haustein,* S. Katcoff,* M. J. LeVine,* Y. Miake,* J. Olness,* L. P. Remsberg,* A. Shor,* M. Tanaka,* M. J. Tannenbaum,* M. Torikoshi,* J. H. van Dijk,* P. Vincent,* H. Wegner,* S. Nagamiya,† W. A. Zajc,† T. Sugitate,‡ H. Crawford,§ D. Greiner,§ P. Lindstrom,§ M. Bloomer,‖ B. Cole,‖ J. Costales,‖ H. A. Enge,‖ L. Grodzins,‖ H. Huang,‖ R. J. Ledoux,‖ R. Morse,‖ C. Parsons,‖ M. Sarabura,‖ S. G. Steadman,‖ G. Stephans,‖ E. Vulgaris,‖ V. Vutsadakis,‖ D. Woodruff,‖ Y. Akiba,¶ H. Hamagaki,¶ S. Hayashi,¶ S. Homma,¶ Y. Ikeda,¶ K. Kurita,¶ M. Naito,¶ and H. Nakamura,¶ T. Abbott,° S. Y. Fung°)

The objective of the experiment, the first relativistic heavy-ion experiment at the AGS, is to study semi-inclusive spectra of p, π, K, d using a single-arm magnetic spectrometer. Particle production cross sections and effective temperatures will be deduced under different impact parameter conditions as determined from measurements of charged-particle multiplicities (M) and transverse energy of neutral particles (E_t). Preliminary results on M and E_t distributions in reactions with 14.6-GeV/A ^{16}O on targets of Au, Cu and mylar were obtained in a first test run. The energy distributions in E_t of O + Au can be described as convolutions of p + Au spectra weighted by a simple

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geometrical model for the reaction. The highest energies observed in E_t (40-60 GeV) for a range in pseudo rapidity of -0.5 to 0.7 can be identified with central collisions. From these data one can deduce that roughly half the beam energy is emitted into this rapidity region, and the incoming O for central collisions is fully stopped in Au at 15 GeV/A.

A short data run has been completed this spring with an almost complete setup for the experiment. From the data will be obtained the cross sections for the particle production, which will form the basis for further data taking with selective triggers for measurements of two-particle correlations and rare-particle events.

The group at Argonne has been working on the coordination of the electronic signals from the various partitions, on setting up the fast trigger logic for the experiment, and for programming of the Fastbus segment manager. Argonne is also responsible for coordinating and setting up the off-line data-analysis package for the experiment.

C. WEAK INTERACTIONS

The main goals of the weak-interactions program are to verify the implications of the Standard Model and to discover its inadequacies.

The search for neutrino oscillations at LAMPF collected data for the first time during 1986. Limits on neutrino oscillation parameters are being evaluated based on 20 days of data collection. This experiment should eventually be sensitive to very small neutrino mixings and a region of oscillation parameters where hints of an effect have been seen in previous experiments.

The cosmic-ray shield built by Argonne National Laboratory for the neutrino oscillation experiment now serves as a muon detector in a search for cosmic-ray point sources. The shield is used to enhance the signal of those showers produced by high-energy photons. This realm of astrophysical observation is extremely exciting and there are possibilities that new physics is the cause of some point-source signals.

The study of neutron beta decay is a developing part of the program. In the past we obtained the most precise value of g_A/g_V from measurements of the asymmetry parameter. This year we made direct measurements of the neutron lifetime to 2%. The new lifetime measurements are consistent with our asymmetry measurements if we take the value of g_V from nuclear beta decay. In addition to its consequences for weak interaction theory, this work has important implications for astrophysics and cosmology.

Our study of the ^{8}Li beta spectrum has important implications for the solar neutrino puzzle because it puts the expected neutrino flux from the sun on a firmer foundation. Other work with beta decay from polarized nuclei studies the effects of induced currents in the weak interaction. These studies have become a traditional part of the program.

To better pin down the vector coupling constant which determines the Cabibbo angle, we are measuring the partial lifetime of ^{10}C decay to the excited 0^+ level of ^{10}B. In the context of the Kobayashi-Maskawa theory, a precise value of this fundamental parameter can be used to determine the number of generations of quarks and leptons.

Finally, our interest in searching for new particles continues. This year we searched for axions from neutron capture on protons using the apparatus to study neutron beta decay. In recent years we searched for magnetic monopoles and light Higgs particles.

a. **Neutrino Oscillations at LAMPF** (S. J. Freedman, J. Napolitano, R. Carlini,* C. Choi,† J. Donahue,* A. Fazely,† B. Fujikawa,‡ G. T. Garvey,* R. Harper,§ R. Imlay,† K. Lesko,‖ T. Y. Ling,§ R. D. McKeown,‡ W. Metcalf,† J. Mitchell,§ E. Norman,‖ T. Romanowski,§ V. Sandberg,* E. Smith,§ and M. Timko§)

Experiment E-645 is a search for $\bar{\nu}_e$'s produced in the LAMPF beamstop. The beamstop is a copious source of ν_μ, and ν_e but a $\bar{\nu}_e$ signal would suggest a transition from one of the other neutrino types. The detector system is an approximately 15-ton fiducial tracking detector made from 40 layers of liquid scintillator and 80 layers of proportional drift tubes. The inner detector is completely surrounded by a 15-cm-thick liquid scintillator active cosmic-ray shield and a 15-cm-thick passive lead shield built by Argonne National Laboratory. The entire system is operated in a tunnel, eventually under 2500 g/cm^2 of overburden, about 20 meters from the LAMPF beamstop. The $\bar{\nu}_e$ detection method is inverse beta decay on the proton and the experimental signal is the final-state positron (maximum energy about 52 MeV). Each scintillator layer is covered with a thin sheet of gadolinium and an available option is to detect the final-state neutron to reduce backgrounds.

The neutrino oscillation detector was exposed to the LAMPF beamstop neutrino source for the first time this year. After the initial shakedown runs it was discovered that the beamstop had inadequate neutron shielding. Extra shielding was installed at the front end of the detector tunnel as a temporary solution. This reduced beam associated background by a factor of five and allowed the run to proceed, but a more complete solution to the shielding problem must be implemented before the next running cycle. The overburden above the tunnel was increased as the run cycle proceeded and the information about the effect on the cosmic-ray neutral background will determine how the remaining shielding material should be distributed. In all, 20 days of stable data taking were obtained under the best conditions practical for this stage of the experiment. The run ended in December 1986,

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and the data are now being analyzed, but there are several conclusions that already can be made.

The active cosmic-ray shield (the primary ANL hardware responsibility) has an inefficient region along the seam where the two sections of the cylindrical shield is joined. The resulting backgound is not now a serious problem but a solution was prototyped and tested during the run. Otherwise the active shield performed up to expectations. Some improvements will be made before the next running cycle. New counters will probably be installed along the inefficient seam. We are also considering a new computer-operated high-voltage distribution system to make the shield easier to operate.

About 10% of the neutrino detector components failed during the run. The detector and shield will be pulled from the tunnel in March for repairs and improvements.

The data are being analyzed for conclusions about neutrino oscillations and we expect to produce limits based on the 20 days of running this year. Work is proceeding to insure that the next running cycle will produce 150 days of useful data.

b. Search for Cosmic-Ray Point Sources (S. J. Freedman, J. Napolitano, B. Fujikawa,* K. Lesko,† E. Norman,† and the Los Alamos Cygnus collaboration: University of Maryland, University of California at Irvine, and Los Alamos National Laboratory)

One of the most exciting discoveries in recent years is cosmic-ray point sources. This discovery is expected to be crucial for understanding the mysterious origin of high-energy cosmic rays in general. The Argonne National Laboratory weak-interactions group has recently joined the "Cygnus" collaboration at Los Alamos which operates a large surface array of plastic scintillators capable of determining the incident direction of cosmic-ray primaries with about 0.5° resolution from timing the resulting shower front arrival. The E-645 active shield is now operated in conjunction with the shower array to provide information about the muon content of point source

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cosmic-ray showers. Since it is expected that the point-source observations are from high-energy photons, the resulting showers should be muon poor relative to ordinary proton-produced cosmic-ray air showers thus, excluding showers for which muons are detected should enhance point-source signals. Runs with a smaller active shield from the E-225 neutrino detector already indicate that this technique improves the signal of Cygnus X-3. The larger E-645 shield is expected to significantly increase sensitivity. This experiment can be run throughout the year and simultaneously with the neutrino oscillation experiment.

The shield was connected to the shower array in early January and the necessary analysis software is now being developed.

c. **Neutron Beta Decay** (S. J. Freedman, M. Arnold,* J. Doehner,* D. Dubbers,† and J. Last*)

During this year's running at the ILL the neutron lifetime was measured using PERKEO (a superconducting solenoidal spectrometer previously used to study the beta asymmetry to measure g_A/g_V). These measurements are particularly interesting because there are serious discrepancies among the existing direct lifetime measurements; results with 1-2% errors disagree by nearly 15%. Two different neutron beam methods were used.

In method one the cold neutron beam was chopped so that single neutron bunches were completely contained inside PERKEO's active volume. Thus for a short time the measured beta-decay rate is independent of the neutron velocity spectrum. The absolute neutron flux was measured with two types of nearly-totally-absorbing thick beamstops made from high-purity gold and cobalt. The resulting activity was measured at several precision counting facilities in Europe and the United States. We obtain $\tau = 880 \pm 17$ s. for our preliminary neutron lifetime. This is in reasonable agreement with $\tau = 898 \pm 6$ s. indirectly inferred from our recent measurements of the beta asymmetry. The error in the present determination is both statistical and systematic but we believe the systematic error cannot be reduced. The results of the present measurement are being prepared for publication.

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In method two a continuous cold beam was used and the flux was measured in "1/v" - detectors. We used both in a ^{3}He-proportional detector and thin gold foils. This method is sensitive to the exact size of the active volume of PERKEO. The analysis is not completed but we expect the lifetime determination will be limited by systematic errors of about 2%, giving a precision similar to method one.

Our two methods give directly-measured lifetimes with about the same experimental errors as previous beam experiments. It is satisfying that the direct lifetime result is consistent with our previous value for g_A/g_V. From the directly-measured lifetime and the beta asymmetry one can determine g_A and g_V.

A long paper describing the experiments that measured the beta asymmetry was completed; a technical paper on the PERKEO spectrometer is being written. Work to develop new neutron decay experiments continues and we are concentrating on an experiment to study possible time-reversal violating asymmetries and a better electron asymmetry measurement. New experiments are expected to be ready in early 1988.

d. **The Vector Weak Coupling and ^{10}C Superallowed Beta Decay**
(S. J. Freedman, R. Holzmann, J. Napolitano, J. Nelson, M. Kroupa,* and P. Barker†)

The best values of the vector weak coupling constant g_V now comes from $0^+ \rightarrow 0^+$ superallowed nuclear beta decay. In principle the best experiment in nuclei is the decay of ^{10}C because of its relative insensitivity to radiative corrections. Unfortunately the experimental error in the branching ratio of the ^{10}C groundstate to the 0^+ excited state of ^{10}B is large and the best determinations now come from higher-Z systems. We are remeasuring this branching ratio to 10^{-3} with an experiment being conducted at the EN tandem of Western Michigan University. The experiment determines the branching ratio from measurements of the cascade γ-rays following beta decay. The critical γ-ray efficiency calibration uses an in-beam method in which inelastic scattering on ^{10}B is used to excite the 0^+ level. By measuring the γ-rays in coincidence with backscattered protons of the right

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energy, the necessary relative calibration is accomplished in exactly the same geometry as the decay measurement.

A special data-acquisition system based on a LSI-11 system was developed for this experiment. The experimental apparatus including two 25%-intrinsic Ge-detectors and an annular Si-detector is installed in nearly its final configuration at Western Michigan University. Preliminary runs give the branching ratio to the 2-3% level routinely in a few hours. Making a 1% measurement easily and routinely is a necessary first step to the order-of-magnitude improvement we desire. Improvements to the experiment are proceeding well and we are studying and eliminating the many systematic effects that must be controlled for the final measurement. Long production runs are being planned for 1987.

e **The Decay of Polarized Nuclei and the Decay Asymmetry of ^{8}Li**
(S. J. Freedman, J. Napolitano, R. Bigelow,* and P. A. Quin*)

The measurements of beta asymmetry parameters in selected nuclear systems is sensitive to many important properties of the weak interaction In some decays the beta asymmetry is sensitive to possible and expected induced currents. We continue to apply the method of polarizing radioactive nuclei in reactions with polarized projectiles in order to study these important effects.

Data from an initial experiment at the Wisconsin Tandem to study the beta asymmetry in polarized ^{8}Li decay have been analyzed. The low beta energy discrepancy in the beta asymmetry found in a previous experiment is much reduced confirming that the problem is caused by systematic error. A new version of the ^{8}Li experiment is being prepared to run in 1987. We expect this work will lead to other applications on this technique of producing nuclear polarization.

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f. **Search for Short-Lived Axions Emitted from Neutron Capture on Protons** (S. J. Freedman, M. Arnold,* J. Doehner,* D. Dubbers,† and J. Last*)

In order to explain the sharp positron emission lines seen in particular heavy-ion collisions at the GSI, several theorists have modified the standard axion theory to make the axion a candidate cause of the unexplained phenomena. The new "viable" axion would be very short lived and have a mass larger than two electron masses. A particularly sensitive way to search for this new particle is the isovector transition in n + p capture. The variant axion would produce an e^+e^- emission signal far larger than that expected from ordinary direct-pair emission. We searched for this enhanced-pair emission during the course of our experiments to measure the neutron lifetime (see Section I.C.c.). The only modification necessary to the PERKEO spectrometer was to add a thin plastic target at the center of the spectrometer. With a cold neutron beam hitting the target we searched for pair emission by recording coincidences between the two plastic scintillators at either end of PERKEO. We observed the expected rate from ordinary pair emission and put strong limits on axion emission.

The early results of this experiment were published in the proceedings of the Heidelberg Conference on Weak and Electromagnetic Interactions in Nuclei and a more complete paper is being prepared for publication.

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g. **The β-decay Spectrum in the A = 8 System and the Solar Neutrino Problem** (J. Napolitano, and S. J. Freedman, and J. Camp*)

The only available experimental result for the flux of solar neutrinos is from Davis, et al. who report a value some three standard deviations smaller than the expected theoretical result. The measured flux is essentially entirely due to high-energy neutrinos from the β-decay of ^{8}B. Consequently, the spectrum of neutrinos from this β-decay is crucial to the calculation of the expected flux, particularly since the final state in ^{8}Be does not have a definite energy. This final state, however, is unstable to 2α decay. The neutrino spectrum is therefore derived from the α-energy spectrum

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using certain reasonable assumptions. However, there is reason to believe that the measured α-spectra at low energies (corresponding to high neutrino energies) are in error. Indeed, various measurements of this spectrum show discrepancies with each other.

Using the Argonne high-energy β spectrograph we have measured the beta spectra of ^{8}Li and ^{8}B. These nuclei were produced using beams from the Physics Division Dynamitron via ^{7}Li(d,p)^{8}Li and ^{6}Li(^{3}He,n)^{8}B. The measured shapes of these beta spectra agree with each other and with a recently-measured α spectrum including target-energy-loss corrections. Thus, we predict no change to the expected theoretical flux. Publication of this work has been delayed for want of a detailed theoretical description of radiative corrections to the neutrino spectrum; however, publication is now imminent.

h. **Search for a Light-Scalar Boson Emitted in Nuclear Decay**
(J. Napolitano, S. J. Freedman, R. Gilman, and J. Nelson)

Using the Physics Division Dynamitron to produce ^{4}He (0^{+}, 20 MeV) via radiative capture of protons on a tritium target, we performed a sensitive search for Higgs-like scalar particles with masses between 3 and 14 MeV/c^{2}. This work has been published. As pointed out in that publication, uncertainties in the theoretical interpretation strongly suggest that a more sensitive experiment be performed.

A number of straightforward modifications to the last experiment would increase the sensitivity by as much as an order of magnitude. However, much greater sensitivity would be achieved if the cosmic-ray background in the detector system were reduced. Using a segmented detector for the $e^{+}e^{-}$ pair (emitted in the decay of the scalar) it appears to be possible to minimize the cosmic-ray background problem by enhancing the signature for the signal relative to that of residual cosmic rays. The Dynamitron remains the optimum accelerator on which to perform this experiment. We have located a 7 × 7 array of NaI(Tl) crystals, each 2.5" × 2.5" × 20", which appears to be a very suitable detector on the basis of Monte Carlo calculations. We are in the process of trying to borrow this system for use at Argonne.

1. **Measurement of the Electric Dipole Moment of the Neutron**
(M. S. Freedman, G. R. Ringo, T. W. Dombeck,* J. M. Carpenter,† N. Jarmie,* and J. W. Lynn‡)

The ultimate purpose of this project is to measure the electric dipole moment (EDM) of the neutron. Such a measurement would probably constitute the most sensitive test of time-reversal symmetry now available. The present situation is that with about a factor-of-10 improvement in sensitivity, a whole class of gauge theories — those which explain CP failure by introducing a new scalar field — can be given a definitive test. Since 1970 it has been clear that this measurement can best be done on ultracold neutrons (UCN) which have a velocity <7 cm/sec and can be stored in a bottle for several minutes. We propose to do this using a pulsed neutron source. We would keep the inlet to the bottle open only when the pulsed source is on, thus allowing a buildup to an asymptotic density determined by the peak flux of the source instead of the average. This has the advantage that pulsed sources have peak fluxes that are much higher than the average fluxes of steady-state sources of the same average power. Second, we propose to produce the UCN by Bragg reflection of considerably faster (400 m/s vs. 7 m/s) neutrons from a moving crystal designed so that the reflected neutrons are almost stationary in the laboratory system. The advantage of this is that it avoids the problems of extracting the very delicate UCN from the hard-to-control environment in a high-flux source. The present state of the project is that both of these ideas have been tested and shown to be practical, as have several other ideas for enhancing the production of UCN, such as the use of reflectors around the moving crystal and funnels to concentrate the UCN in real space at the expense of their concentration in velocity space.

Since the LAMPF accelerator at Los Alamos has the highest pulsed-current proton beams available anywhere at energies >200 MeV, it can produce, and indeed we have produced, the highest peak neutron fluxes that are available. These will not be produced on a regular basis until 1988, but it is proposed to set up the EDM experiment at this source, which is now called LANSCE. In the meantime we have built an improved moderator using solid

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methane at 15°K, which should produce several times as high a flux of the relevant neutrons (100 to 400 m/sec) as any sources hitherto available. We are also developing an improved system for converting cold to ultracold neutrons using an artificial crystal (multilayer). Recent improvements at the pulsed neutron source at Argonne, IPNS, make it quite useful for development of components of the EDM experiment and we have set up a beam line there to test these conversion systems, and guide tubes, valves and bottles.

II. RESEARCH AT ATLAS

The heavy-ion research program in the Physics Division at Argonne is conducted with ATLAS, the Argonne Tandem Linac Accelerator System. Since ATLAS was completed in September 1985 beam time has been available on a regular basis and the emphasis has shifted from construction of equipment and beam lines to research. There is a continuing effort devoted to the completion of the experimental equipment and the initiation of the next generation of apparatus. Beam time is allocated with the advice of a Program Advisory Committee and a substantial fraction of experiments (2/3) now involve outside users.

The research program addresses the dynamics of heavy-ion collisions, the structure of nuclei at high spin and temperature, and the interplay between the two. The division of the total reaction cross section into peripheral events and fusion, the balance between quasifission and fusion, and the decay of the compound nucleus itself, all appear to be influenced by subtle effects of nuclear structure. A fair portion of our current and future program is aimed at this experimental connection between nuclear structure and dynamics.

In the study of nuclei at high spin the focus at Argonne is on mapping the change of nuclear structure with spin, internal excitation energy (i.e. energy above the yrast line) and nucleon number, within a coherent framework. The experiments concentrate on properties of nuclei both near the yrast line and in the high-lying continuum region, and try to relate structures in the yrast region of deformed nuclei to excited states in nearby spherical nuclei. The new BGO gamma-ray facility has been used in experiments and has led to important new results. Dramatic shape changes along the yrast line have been observed in several nuclei through identification of levels with spin up to $46\hbar$ and measurement of their lifetimes. The high resolution and sensitivity of the apparatus has made it possible to quantitatively understand the gamma deexcitation cascade and to elucidate the change in nuclear structure from the oblate coupling scheme near the yrast line to a rotational one, with increasing temperature and spin. In a novel application of the gamma-ray facility, gamma rays from a fission source were measured and led to the discovery of octupole shapes at medium spin ($>7\hbar$) in neutron-rich Ba nuclides that cannot otherwise be studied with reactions. Groups from Notre Dame and Purdue actively participate in these measurements.

A systematic study of quasielastic reactions with heavy projectiles has been carried out with ATLAS coupled to an Enge split-pole spectrometer and detectors combining E-ΔE measurements with good position and timing resolution. This led to the unexpected result that quasielastic scattering (primarily neutron transfer) accounts for a large fraction of the total reaction cross section, especially at low energies. It has also been demonstrated that the transition between quasielastic scattering and strongly-damped collisions is a gradual one; these processes seem to be closely related and not as distinct as was generally believed. The transition may be represented as a change from a simple one-step process, through multi-step exchange of nucleons, to a complex statistical reaction, whose limiting case may be fusion. A simple random-walk model has proved very successful in describing this picture. Another set of recent measurements has shown, for the first time, the surprising result that even at incident energies below the

Coulomb barrier the strongly-damped process represents a significant fraction of the cross section, comparable to fusion.

Many facets of fusion are investigated. Cross-section measurements for fusion as well as for quasielastic transfer channels for the Ni + Ni and Ni + Sn systems led to the observation of a correlation between large quasielastic reaction strengths and large sub-barrier fusion enhancement. There is also probably a connection with an unexpected result which shows large deep-inelastic cross sections near the barrier. These findings suggest that transfer channels, as well as inelastic channels, should be included in coupled-channel calculations which aim to explain sub-barrier fusion. Limitations to fusion arise for heavy systems because of the Coulomb repulsion between the interacting ions which, instead of fusing, reemerge after exchanging nucleons and drifting towards mass symmetry--a process referred to as quasifission. Work at Argonne, as well as at GSI with active Argonne participation, has shown that the reaction time for this process is strikingly independent of excitation energy, pointing to a one-body dissipation mechanism in nuclear interactions. This result is consistent with a mean free path longer than nuclear dimensions.

At higher bombarding energies only a part of the incident projectile (or target) fuses — a process known as incomplete fusion. Argonne work in the past year has sought to understand the process and to discriminate among several models through extensive coincidence measurements between evaporation-like residues and light charged particles and between the light particles. The latter can give information on the time- or spatial-scale involved in the reaction. Groups from Hope College, University of Kansas, SUNY Stony Brook, Vanderbilt University and the Weizmann Institute have active programs in this area.

In light systems another possible explanation for the limitation of fusion is that a compound nucleus is actually formed, which subsequently fissions and thus does not appear as a component of evaporation residues. Indeed, work at Argonne suggests that such a fission process does occur for the A=56 system. Coincidences between the fragments and gammas have been measured using the BGO gamma facility, with the aim of identifying the types of states populated in the fully-damped fragments and to thus infer the nature of the pre-fission states. A last aspect of the fusion program concerns the decay of the compound nucleus, where we have an on-going systematic study of the shape-relaxation process. The time scale for this relaxation may be 3 orders of magnitude slower than expected, leading to a suppression of neutron emission. Experiments to pinpoint the cause of this suppression focus on measuring the partial-wave distributions, identifying the gamma-ray component which removes the energy not otherwise removed by the neutrons, and probing the shape of the emitting nucleus through alpha energy spectra.

Important advances have been made at ATLAS in accelerator mass spectrometry using the full tandem-linac accelerator and the gas-filled spectrograph, thus making it possible to detect and identify heavy isotopes, e.g. ^{41}Ca and ^{60}Fe. Other topics include calculations on the possibility of a condensed crystalline state in cooled heavy-ion beams, the emission of heavy clusters such as ^{14}C and ^{34}Si from heavy nuclei, and a measurement to investigate the feasibility of using ^{81}Br for detection of solar neutrinos, a measurement of the atomic charge-state dependence of nuclear lifetimes, using the 14-keV state in ^{57}Fe.

Several major experimental facilities have been constructed to utilize the beams from ATLAS. These include (a) beam lines with diagnostics and beam-handling components to make optimal use of the good beam properties; (b) a general-purpose scattering chamber with provisions for attaching large vacuum extensions; (c) a γ-ray facility, constructed jointly by Argonne and Notre Dame, at present with 8 Compton-suppressed Ge detectors (CSG) and 14 BGO hexagons as a multiplicity filter; (d) an Enge split-pole spectrograph (relocated from the old tandem area and refurbished for detection of heavy ions; (e) general-purpose beam lines, where temporary equipment can be installed, including an atomic-physics beam line; and (f) new large-area HI detectors, including a modified Breskin-type detector capable of ~150 ps timing, parallel-plate avalanche detectors, a Bragg-Curve Spectrometer with good timing and spatial resolution. In addition, a new data-acquisition system (DAPHNE), with an architecture based on parallel processors, was developed to handle the acquisition and analysis of the new generation of experiments; software additions and improvements have been made to expand the capability of the system.

The second phase of equipping the ATLAS experimental area is now under way. Scattering chambers are now being designed to enable coincidence measurements between components of the BGO gamma facility and the Enge spectrograph and for charged-particle coincidences with the gamma facility. Design studies have been completed for a Fragment Mass Analyzer (FMA) for the separation and detection of reaction products. With good A/Q resolution (1/300) and very large detection efficiency (up to 40% in some cases), this device will open up many new classes of experiments. Tests will be conducted to determine the feasibility of sustaining the high electric fields which are part of the design. A new data-acquisition system, based on coupling DAPHNE to a micro-VAX, is being constructed. It will be used for taking data in target Area II, as well as for Target Area III (where it will relieve the heavy load on the present system by permitting more flexibility in testing equipment and in setting up experiments); in addition it will be used as a play-back station for data analysis.

A. QUASIELASTIC PROCESSES AND STRONGLY-DAMPED COLLISIONS

The availability of heavier beams and higher energies from the ATLAS accelerator has increased the range of experiments performed during the last year. Many of the experiments focus on the quasielastic processes, which have been found to be unexpectedly strong near the Coulomb barrier, and on their influence on other reaction channels. From the experiments performed so far, a systematic trend and a semiclassical picture have emerged, which can describe the neutron transfer reactions for a large variety of systems covering two orders of magnitude in cross section. Furthermore, cross sections for reactions involving very heavy ions (U,Pb,Th..) are in good agreement with these systematics. The experiments have been extended to heavier projectiles (^{80}Se) and to higher and lower energies, where new detection techniques had to be developed. In particular, the system Ni + Sn has been studied in great detail. At sub-barrier energies, the recoil mass separator at Daresbury was used in order to measure the magnitude of the neutron-transfer cross section. Measurements at the Coulomb barrier for O- and Ni-induced reactions on Sn nuclei performed here at Argonne showed a strong correlation between the sub-barrier fusion enhancement and the strength of the quasielastic cross section. This indicates that quasielastic reaction channels might be important doorway states toward fusion. Similar correlations are also found in the Ni + Ni system where we have extended our previous measurements into the true sub-barrier region using time-of-flight techniques in the split-pole spectrograph. Another unexpected result was the observation of a large deep-inelastic cross section (comparable in size with the fusion cross section) in the system ^{58}Ni + ^{112,124}Sn at and below the Coulomb barrier. For this experiment, kinematic coincidence techniques with newly-developed parallel-gridded avalanche detectors were used.

With the higher energies from ATLAS we have begun spectroscopic studies with heavy-ion reactions in previously-unexplored energy regimes. The two-particle transfer reaction ^{90}Zr(^{16}O,^{14}C)^{92}Mo was studied at 80, 140 and 200 MeV with good resolution using the split-pole spectrograph. This experiment was performed in order to understand the large deviations between the measured cross sections and the DWBA predictions.

A new class of experiments as the borderline between nuclear and atomic physics was started with an investigation of the dependence of the nuclear lifetime of the atomic charge state. The first experiment concerned the 14.4-keV state of ^{57}Fe. This state was populated using Coulomb excitation by a thin Au target and the charge state was analyzed with the split-pole spectrograph. Such experiments yield new information about inner-shell electron properties in highly-stripped atoms, and their influence on nuclear lifetimes.

a. **Energy Dependence of the Two-proton Tranfer Reaction $^{90}Zr(^{16}O,^{14}C)^{92}Mo$** (K. E. Rehm, B. G. Glagola, W. C. Ma, W. R. Phillips,* and F. L. H. Wolfs†)

One-particle transfer reactions are generally well understood within the framework of one-step DWBA calculations using spectroscopic factors from light-ion experiments. Two-particle transfer on the other hand, in particular two-proton transfer reactions, are generally several orders of magnitude larger than predicted by the DWBA theory. We have studied the energy dependence of the two-proton transfer reaction $^{90}Zr(^{16}O,^{14}C)^{92}Mo$ in the energy range E_{lab} = 80-200 MeV. With a 5-slit entrance aperture and ray-tracing techniques, 5 angles could be measured simultaneously. Fig. II-1 shows preliminary angular distributions for the $^{90}Zr(^{16}O,^{14}C)$ reaction at E_{lab} = 138.2 MeV and 194.4 MeV, respectively. The solid lines are one-step DWBA calculations performed with the code PTOLEMY, and normalized to the experimental data. It is observed that the enhancement of the experimental cross sections, which is about 600 at E_{lab} = 80 MeV, decreases to ~250 (138.2 MeV) and 90 (194.4 MeV). In the future we plan to investigate the contributions from two-step transfer reactions [$^{90}Zr(^{16}O,^{15}N)^{91}Nb$; $^{91}Nb(^{15}N,^{14}C)^{92}Mo$] in more detail.

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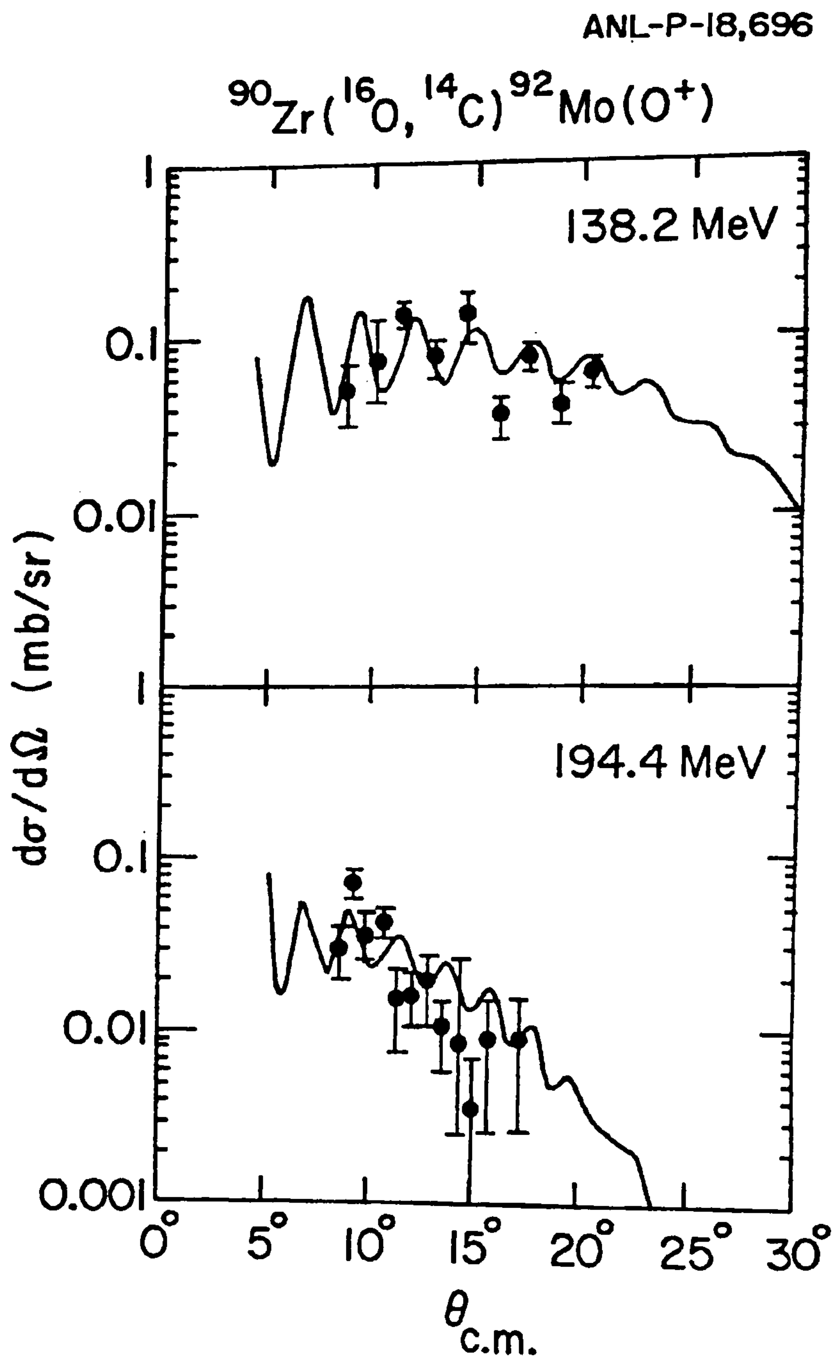

Fig. II-1. Angular distributions for the two-proton transfer reaction $^{90}Zr(^{16}O,^{14}C)^{92}Mo$ at 138.2 MeV and 194.4 MeV. The solid lines are one-step DWBA calculations.

b. **Quasielastic Reactions of ^{28}Si with ^{208}Pb** (J. J. Kolata,* R. J. Vojtech,* D. G. Kovar, and K. E. Rehm)

Quasielastic processes (elastic and inelastic scattering and few-nucleon transfer) have been measured for the ^{28}Si + ^{208}Pb reaction at E(^{28}Si) = 6 MeV/nucleon and 8 MeV/nucleon corresponding to 1.3 and 1.75 times the Coulomb barrier. The data are characterized by large cross sections for the quasielastic transfer reactions. For example, the single-neutron pickup reaction alone contributes 12% of the total reaction cross section at 8 MeV/nucleon, and 29% at 6 MeV/nucleon. All of this strength is concentrated in a few states at excitation energies of 0-5 MeV above the ground state. The other main constituents of the measured quasielastic yields, the two- and three-neutron pickup and one-proton stripping processes, are also quite large, contributing 8% of the total reaction cross ection at 8 MeV/nucleon and 16% at 6 MeV/nucleon.

In an extension of this work we have studied the same system at 150 MeV, where the dominance of the neutron-transfer cross sections should be even stronger. The experiment was performed at the split-pole spectrograph with an energy resolution of about 270 keV, allowing studies of transitions to resolved final states in the residual nuclei. The analysis of the data is in progress.

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c. **Measurement of Sub-barrier Reactions using a Recoil Mass Separator**

(R. R. Betts, P. M. Evans,* C. N. Pass,* N. Poffe,* A. E. Smith,* L. Stuttge,* J. S. Lilley,† D. W. Banes,† K. A. Connell,† J. Simpson,† J. R. H. Smith,† A. N. James,‡ and B. R. Fulton§)

The Recoil Mass Separator (RMS) at the Nuclear Structure Facility, Daresbury Laboratory, has been used in a novel manner to measure quasielastic reactions of ^{58}Ni + ^{A}Sn at energies below the Coulomb barrier. These reactions are intrinsically backward peaked in the center-of-mass system and are thus extremely difficult to measure in the conventional way. The RMS was used to detect the associated forward-going target-like recoil with excellent mass resolution. Cross sections for both one- and two-nucleon pickup reactions have been obtained for a number of Sn isotopes at energies as low as 40 MeV below the barrier. Figure II-2 shows the θ_{cm} = 180° cross sections for one-nucleon pickup from $^{124,122,120,118,116}Sn$ plotted as a function of laboratory bombarding energy. The normal Coulomb barrier for these systems is close to 230 MeV. The measured cross sections show a strong isotopic dependence of the measured sub-barrier cross sections. Analysis of these data in terms of both simple schematic models and DWBA gives a good account of the results. It appears that the isotopic dependence results from population of a few strong states of similar structure in each isotope.

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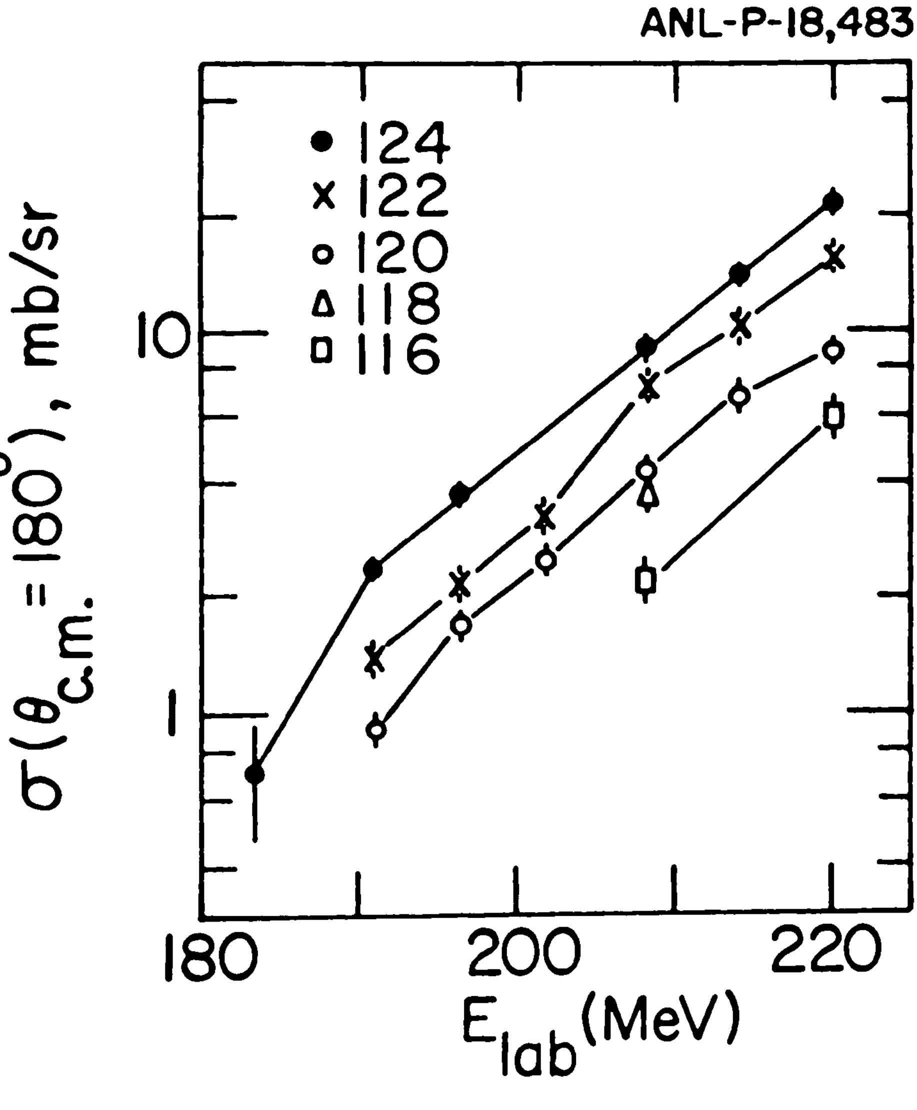

Fig. II-1. Cross sections for one-nucleon pickup reactions at $\theta_{cm} = 180^\circ$ as a function of bombarding energy for $^{58}Ni + {}^{A}Sn$ reactions.

d. **Particle-gamma Coincidence Measurements of Sub-barrier Quasielastic Reactions** (R. R. Betts, C. N. Pass,* P. M. Evans,* A. E. Smith,* J. S. Lilley,† K. A. Connell,† J. Simpson,† J. R. H. Smith,† A. N. James,‡ P. A. Butler,‡ and B. R. Fulton§)

The unique combination of the Daresbury Recoil Mass Separator with a 16-detector array of Compton-suppressed gamma-ray detectors (POLYTESSA) is being used to study the details of the population of final states in sub-barrier quasielastic reactions. The experiments performed thus far are: 1) a study of the ^{58}Ni + ^{124}Sn system in order to provide information on the specific states populated in the one-neutron pickup channel. This information is an essential ingredient in the testing of DWBA and CCBA analyses of the distribution of sub-barrier reaction strength for such heavy-ion systems and in the explanation of the observed sub-barrier enhancement of fusion; 2) a study of final states populated in Coulomb excitation and one- and two-nucleon pickup for the ^{58}Ni + ^{162}Dy systems. The primary aim of this study is spectroscopic, in that the transfer reactions are expected to proceed from excited states of the target following inelastic excitation, thus giving information on transfer matrix elements not otherwise available.

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e. **Strength of Deep-inelastic Scattering Near the Barrier for ^{58}Ni + ^{112,124}Sn** (F. L. H. Wolfs,*)

Very limited information exists on the distribution of the total reaction strength in heavy-ion collisions at energies close to the Coulomb barrier. In order to study this distribution, evaporation residue, fission and quasielastic scattering yields have been measured previously for ^{58}Ni + ^{124}Sn. For both systems a significant part of the total reaction cross section (deduced from the measured "elastic-plus-elastic" scattering angular distributions) is not accounted for by the sum of the partial reaction cross sections. The only reaction mode that could have been missed in the previous

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measurements is one that may be related to deep-inelastic scattering, a process where two fragments with masses close to that of the projectile and target emerge from a strongly-deformed system.

Deep-inelastic scattering cross sections for ^{58}Ni + ^{112,124}Sn have been measured at several bombarding energies between 230 and 290 MeV. These measurements were carried out using the method of kinematic coincidence with two large-area position-sensitive detectors. The mass distributions for events with Q-values more negative than -20 MeV show two distinct components: two peaks centered around masses close to those of the projectile and target and a wide mass distribution centered around half the mass of the compound nucleus, consistent with fission. A typical mass spectrum is shown in Fig. II-3. It also shows toal kinetic energy (TKE) spectra for events with masses between 48 u and 68 u. The arrow indicates the TKE corresponding to the Coulomb repulsion of two touching spherical nuclei. The shape of the lower ends of the TKE spectra is independent of the incident energy and at a TKE of 120 MeV consistent with a deformation in both fragments of up to $\beta \approx 0.65$. Deep-inelastic scattering events have been defined as those with mass close to that of the projectile and target ($|\Delta m|$<10 u) and with a reaction Q-value more negative than -20 MeV.

The total reaction cross sections are in reasonable agreement with the sum of fusion, deep-inelastic and quasielastic scattering yields. For the strength of the different reaction modes we observe that at energies above the Coulomb barrier the partition of the total reaction cross section between the various reaction modes seems constant, with fusion and quasielastic scattering being the dominant modes for ^{58}Ni + ^{112}Sn and ^{58}Ni + ^{124}Sn, respectively. Below the barrier quasielastic scattering exhausts an increasingly larger fraction of the total reaction cross section. While fusion is stronger than deep-inelastic scattering at energies above the barrier, at sub-barrier energies the two are similar in yield.

We plan to continue our study of the Ni + Sn system with measurements of the deep-inelastic scattering cross sections for ^{64}Ni + ^{112,124}Sn. This will allow us to compare the target dependence of deep-inelastic scattering for ^{58}Ni-induced reactions with that for ^{64}Ni-induced reactions.

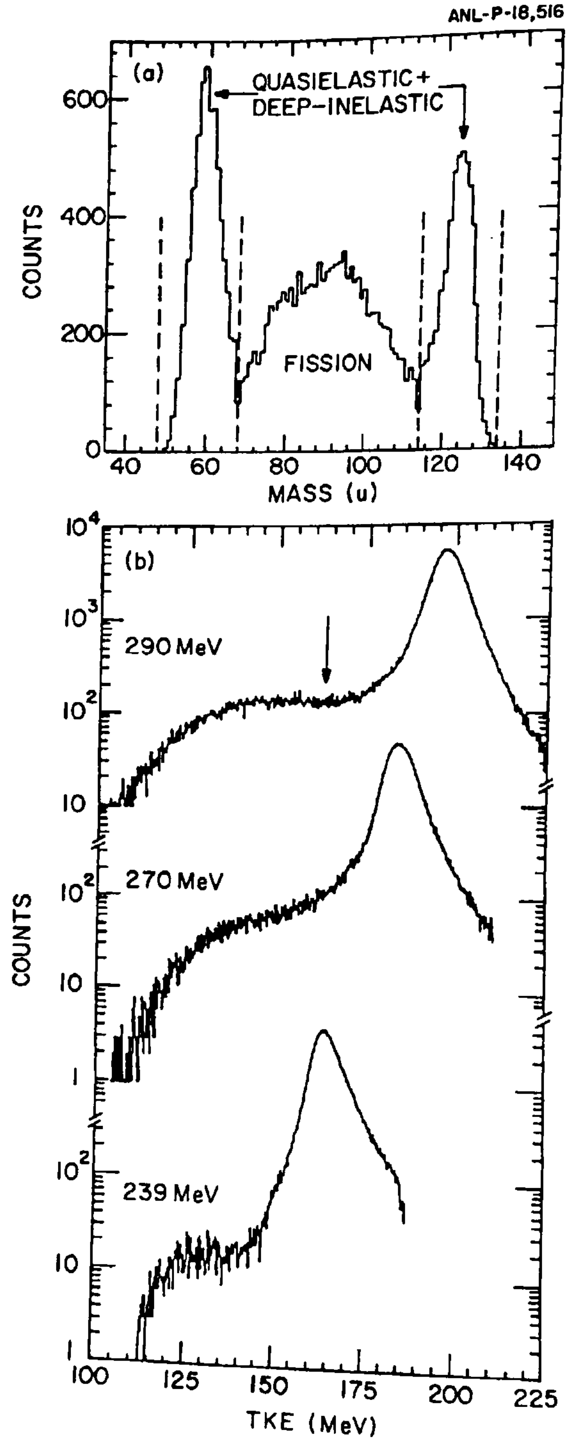

Fig. II-3. (a) Mass spectra of events with Q-values more negative than −20 MeV for $^{58}Ni + ^{124}Sn$ at 290 MeV. (b) Total kinetic energy (TKE) spectra of events with mass between 48 u and 68 u for $^{58}Ni + ^{124}Sn$ at 239, 270 and 290 MeV. The arrow indicates the Coulomb repulsion energy of two touching spherical nuclei.

f. **Quasielastic Transfer for ^{76,82}Se-induced Reactions on ^{192,198}Pt at Energies above the Coulomb Barrier**
(F. L. H. Wolfs, K. E. Rehm, W. C. Ma, J. P. Schiffer, and T. F. Wang)

We have extended our studies of the partitioning of the reaction cross section to the heavier system Si + Pt. Similar to the Ni + Sn case, we have studied the neutron number dependence of the quasi-elastic cross sections for processes induced by ^{76,82}Se on ^{192}Pt and ^{198}Pt. The experiments were performed with 500-MeV Se beams in the split-pole spectrograph. Using time-of-flight techniques with the new position-sensiutive parallel-plate avalance counter in the focal plane, a separation of one- and two-particle transfer reactions from the elastic peak was achieved. Figure II-4 shows the mass dependence of the quasielastic cross section for ^{76}Se- and ^{82}Se-induced reactions. Similar to the ^{58,64}Ni + Sn results, one observes an increase of the quasielastic cross sections with increasing mass for the case of the neutron deficient ^{76}Se while for ^{82}Se the cross sections stay almost constant. For the balance of the cross sections this result implies that the deep-inelastic cross sections for ^{82}Se + Pt are likely to be larger than those for ^{76}Se + Pt.

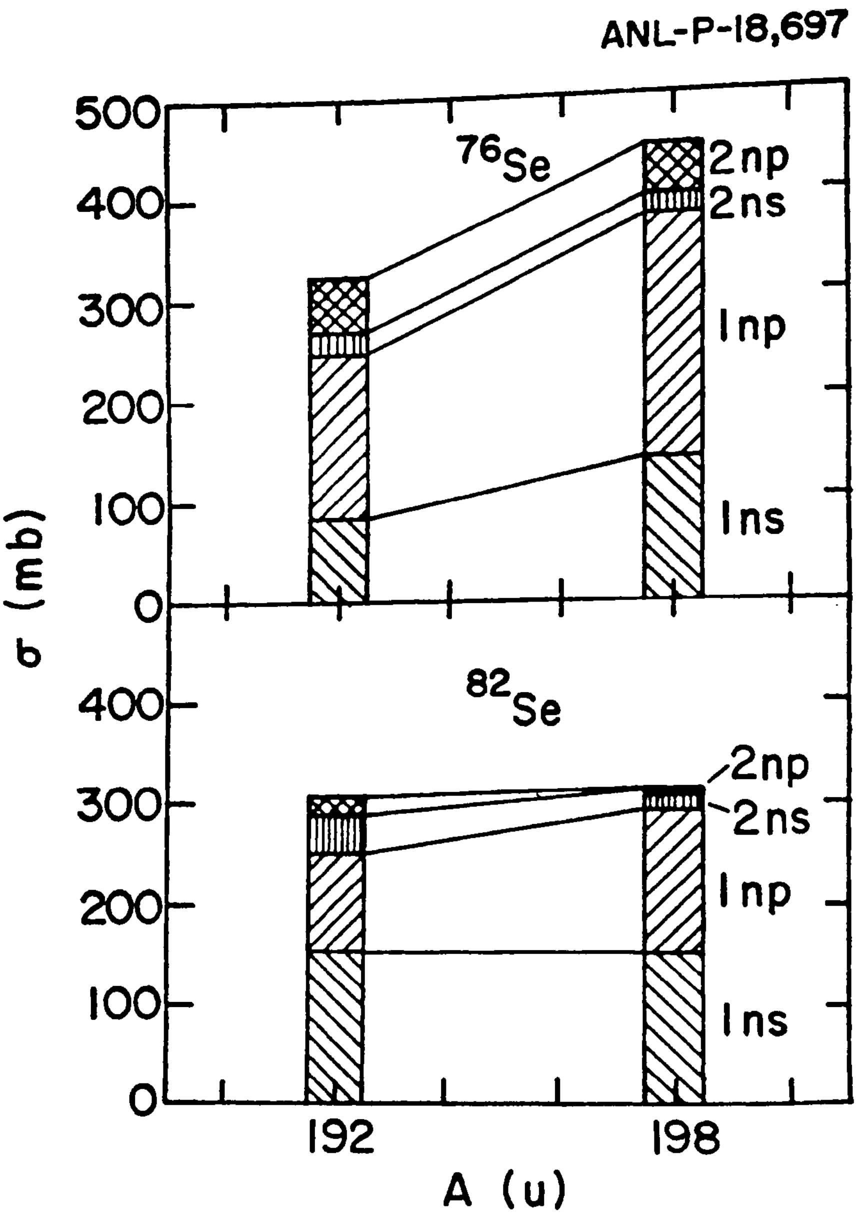

Fig. II-4. Quasielastic cross sections induced by ^{76}Se (top) and ^{82}Se (bottom) on ^{192}Pt and ^{198}Pt. (1p and 2p corresponds to one- and two-particle pickup reactions and 1s and 2s corresponds to one- and two-particle stripping reactions, respectively.)

g. **Sub-barrier Nucleon Transfer: Doorway to Heavy-Ion Fusion**
(W. Henning, F. L. H. Wolfs, J. P. Schiffer and K. E. Rehm)

For the systems $^{16,18}O$ + Sn and ^{58}Ni + Sn, the division of the reaction strengths into fusion, fission and transfer reactions has been measured. The large differences found for the quasielastic transfer cross sections between the systems O + Sn and Ni + Sn correlate directly with the sub-barrier fusion enhancement, suggesting nucleon transfer as an important doorway to fusion. This is shown in more detail in Fig. II-5 where fusion cross sections (circles) and quasielastic cross sections (squares) are compared for Ni- and O-induced reactions on Sn isotopes. The solid lines are the results of one-dimensional barrier penetration calculations, showing the large enhancement for the ^{58}Ni-induced reactions. Simple two-level mixing calculations have been performed for the coupling between fusion and transfer. These calculations indicate that, under the assumption of a constant transfer cross section, negative Q-values can also lead to a large sub-barrier fusion enhancement. A paper with these results has been published.

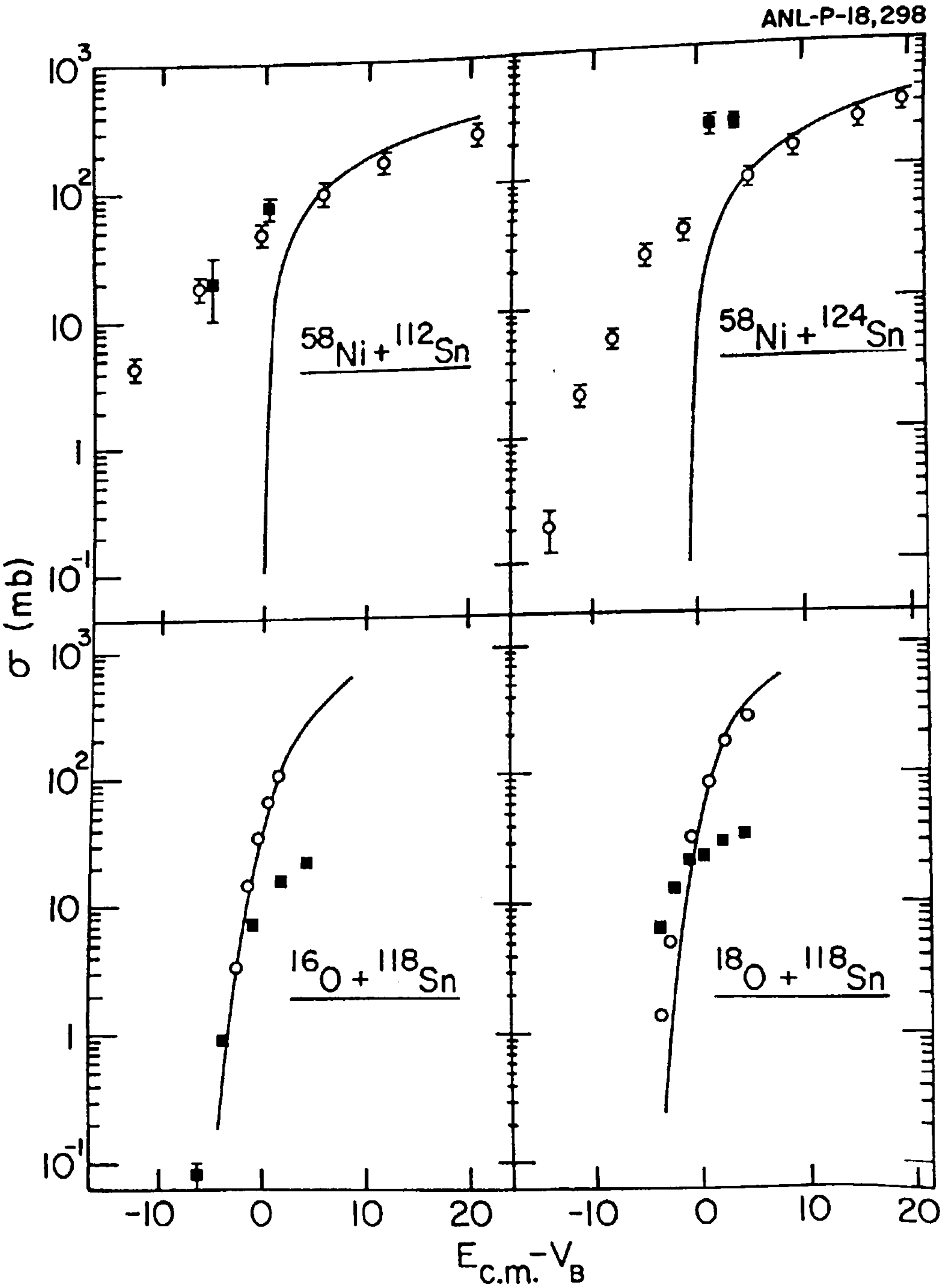

Fig. II-5. Excitation functions for fusion (circles) and quasielastic transfer processes (squares) induced by ^{58}Ni (tip) and ^{16}O (bottom) projectiles on various Sn isotopes. The solid lines are one-dimensional barrier-penetration calculations with the code PTOLEMY.

h. **Systematics of Neutron Transfer Cross Sections in Heavy Systems** (K. E. Rehm, A. van den Berg, D. G. Kovar, W. Kutschera, and J. L. Yntema)

In the last few years a large number of one-neutron transfer cross sections for heavy-ion-induced reactions have been measured. The angle and energy-integrated yields for reactions induced by projectiles ranging from ^{28}Si to ^{64}Ni are shown in Fig. II-6(a) as a function of the ground state Q value Q_{gg}. These cross sections cover almost two orders of magnitude and show an exponential increase but also large fluctuations. The fluctuations arise from the fact that the binding energy of the transferred neutron varies for the cases studied here. Within semiclassical approximations it is found that the integrated cross section σ depends on the binding energy in the initial and final channel like $\sigma \sim (B_i B_f)^{-1.1}$. Multiplying the cross section by $(B_i B_f)^{1.1}$ strongly reduces the fluctuation as shown in Fig. II-6(b). The increase of these "reduced" cross sections with Q_{gg} can be understood from the underlying Q-matching behavior for neutron transfer reactions which gives the solid line in Fig. II-6(b). This systematic can be used to predict one-neutron transfer cross sections for even heavier systems.

i. **Energy Dependence for Quasielastic Reactions** (K. E. Rehm, W. Kutschera, D. G. Kovar, F. Videbaek, and F. L. H. Wolfs*)

We have begun to study the energy dependence of individual reaction channels in heavy-ion-induced transfer reactions in the energy range from below to about twice above the Coulomb barrier. For several systems (Ni + Sn, Ni + Pb, Ni + Ni), one observes for quasielastic neutron transfer reactions a constant cross section at energies above the Coulomb barrier and an exponential falloff at energies below the Coulomb barrier. If compared to the energy dependence of fusion reactions, it is found that in the vicinity of the Coulomb barrier the dominant reaction channels are quasielastic reactions. In particular, for the system $^{58}Ni + ^{208}Pb$ one expects that neutron transfer processes are about 100 times stronger than fusion-fission or quasi-fission reactions at energies of ~320 MeV. At present the energy dependence of the charged-particle transfer cross sections as measured for the system $^{58}Ni+^{208}Pb$ at E_{lab} = 325, 345, 375 and 550 MeV is being analyzed.

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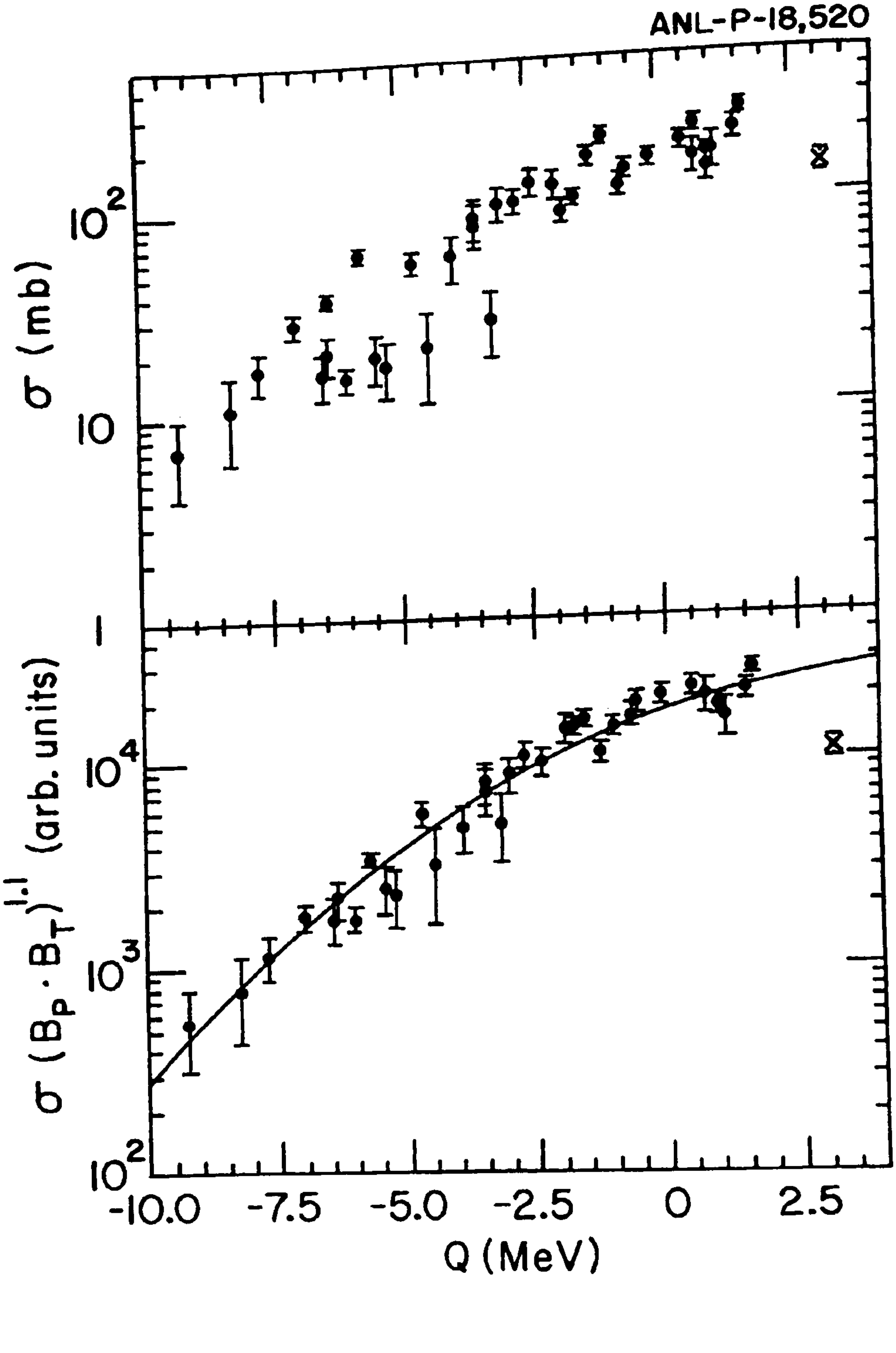

Fig. II-6. (top): Angle- and energy-integrated one-neutron transfer cross sections for reactions induced by $^{28}Si...^{64}Ni$ on various target nuclei as function of the ground-state Q value Q_{gg}. (bottom): reduced transfer cross sections (i.e. multiplied by a function depending on the binding energies in the initial and final channels).

j. **Quasielastic Transfer Reactions in the System $^{80}Se + ^{208}Pb$**
(K. E. Rehm, C. Beck, D. G. Kovar, W. C. Ma, F. Videbaek, M. Vineyard, and T. F. Wang)

With the availability of energetic heavy-ion beams from the ATLAS accelerator, we have extended our studies of quasielastic transfer reactions induced by medium-weight projectiles to the system $^{80}Se + ^{208}Pb$. The experiment was performed with the split-pole spectrograph in the new experimental area. Seven charge states containing more than 90% of the total charge-state distribution could be measured simultaneously. With the existing focal-plane detector it was possible to resolve the one- and two-neutron transfer reactions from the strong elastic reaction in the mass-80 region Angular distributions for elastic scattering (including inelastic excitation to the lowest states in Se and Pb) and for the one- and two-neutron transfer reactions are shown in Fig. II-7.

Similar to the previous studies, it is observed that one-neutron transfer reactions are again the strongest individual transfer channels. The energy- and angle-integrated transfer cross sections agree well with the systematic picture, which evolved from the results of our previous studies (see Sect. A.h.).

k. **Study of the $^{48}Ti + ^{104}Ru$ Single-nucleon Transfer Reaction**
(S. J. Sanders, B. B. Back, R. R. Betts, R. V. K. Janssens, D. Henderson, W. Henning, K.-E. Rehm, and F. Videbaek)

We have measured the single-neutron transfer cross sections for the $^{48}Ti + ^{104}Ru$ system at the Coulomb barrier. It has been speculated that shape isomerism, similar to that established through fission studies in the actinides, may be responsible for certain long-lived, superdeformed states in medium-mass nuclei. Evidence for these states has recently been seen in γ-ray studies.[1,2] A possible particle signature for these structures would be an enhanced cross section at forward angles in single-neutron transfer reactions. Such an enhancement would arise from the compound system becoming trapped in a secondary minimum of the nuclear potential energy surface, thus increasing the interaction time. Choosing a system for which there is evidence in γ-ray studies[1] of shape isomerism, we have measured the neutron-transfer angular distributions for the $^{48}Ti + ^{104}Ru$ system (reaching the ^{152}Dy

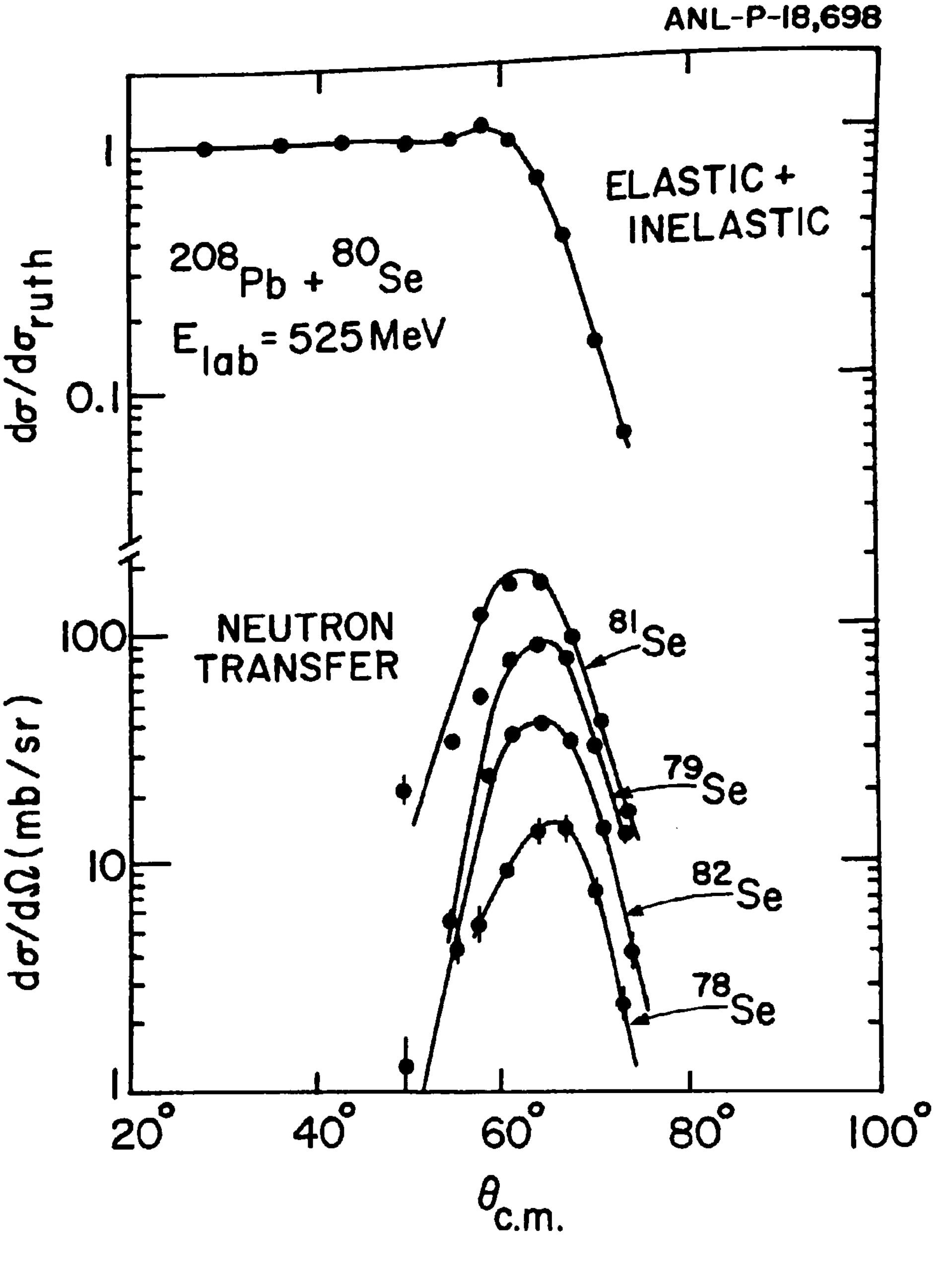

Fig. II-7. Angular distribution for elastic scattering (including inelastic excitation to the lowest states) and for various neutron transfer channels measured in the system $^{80}Se + ^{208}Pb$ at 525 MeV.

compound system). At the barrier energy this distribution would normally be expected to peak at the grazing angle of 180° and a forward-angle enhancement would indicate a time delay in the interaction. For this measurement a multichannel-plate start detector system has been developed for use in the Enge split-pole spectrometer scattering chamber. The timing information obtained from this detector, used in conjunction with information derived from an avalanche-type stop detector located at the focal plane, resulted in good separation of the single-neutron transfer channels. Although we have not completed our analysis of these data, our preliminary analysis indicates no enhancement beyond that predicted by DWBA calculation to the level $\sigma_{1n}/\sigma_{Ruth} \approx 10^{-3}$.

[1]P. J. Twin et al., Phys. Rev. Lett. 57, 811 (1986).
[2]A. J. Kirwan et al., Phys. Rev. Lett. 58, 467 (1987).

ℓ. Charge-state Dependence of the Half-life of the 14.4-keV State in ^{57}Fe (W. R. Phillips, I. Ahmad, B. G. Glagola, W. Henning, K. E. Rehm, and J. P. Schiffer)

We have begun experiments to study changes in the lifetimes of excited nuclear states as the charge of the ions is varied. Suitable nuclear states for study are those with lifetimes in the range from about 20 to 200 ns and whose decay probabilities depend mainly on internal conversion. The experiments thus provide a way to investigate inner-shell electron properties in stripped atoms, as well as the influence of the electronic environment on nuclear decays.

The first experiments concerned the 14-keV first-excited state of ^{57}Fe. This state has a half-life of about 98 ns. The novel technique being developed to measure the changes in lifetime involves using Coulomb excitation by a thin gold target to produce ionic beams of excited $^{57}Fe^{q+}$. Each chargestatge q is studied in turn by magnetic selection in a split-pole magnetic spectrograph. Ions which enter the magnetic field region in a charge-state q, and undergo no charge-changing process, appear as a peak at the position in the focal plane. Some ions will experience internal conversion decay of the 14-keV nuclear level in the magnetic field region. Their charge will increase by one if the electron hole is filled with accompanying X-rays: if the hole is filled with an accompanying Auger electron, q will increase by two units.

Ions resulting from these charge-changing processes will be distributed in the focal plane between the undisturbed charge-state peaks.

The first measurements were designed to obtain information about the experimental techniques. It was observed that the structure of the split-pole spectrograph with its gap between the pole pieces is very useful in distinguishing the single and double charge-changing processes. This is because charge-changing processes which occur in the gap result in peaks in the focal plane. Examples for spectra measured at 7.5° (which show almost no charge-changing processes) and at 35° are shown in Fig. II-8. The satellite peaks, e.g. on the right side of the 24^+ charge state result from charge-changing processes in the almost-field-free gap region.

At the moment there are not enough data to give sufficiently accurate lifetime measurements, although there is suggestion for an increased lifetime in the q=24 state. Furthermore, new results on K-shell fluorescent yields $w_k(q)$ in the different states q have been obtained. It is planned to improve the statistics for ^{57}Fe in an upcoming experiment. An extension of these measurements towards heavier ions is also under consideration.

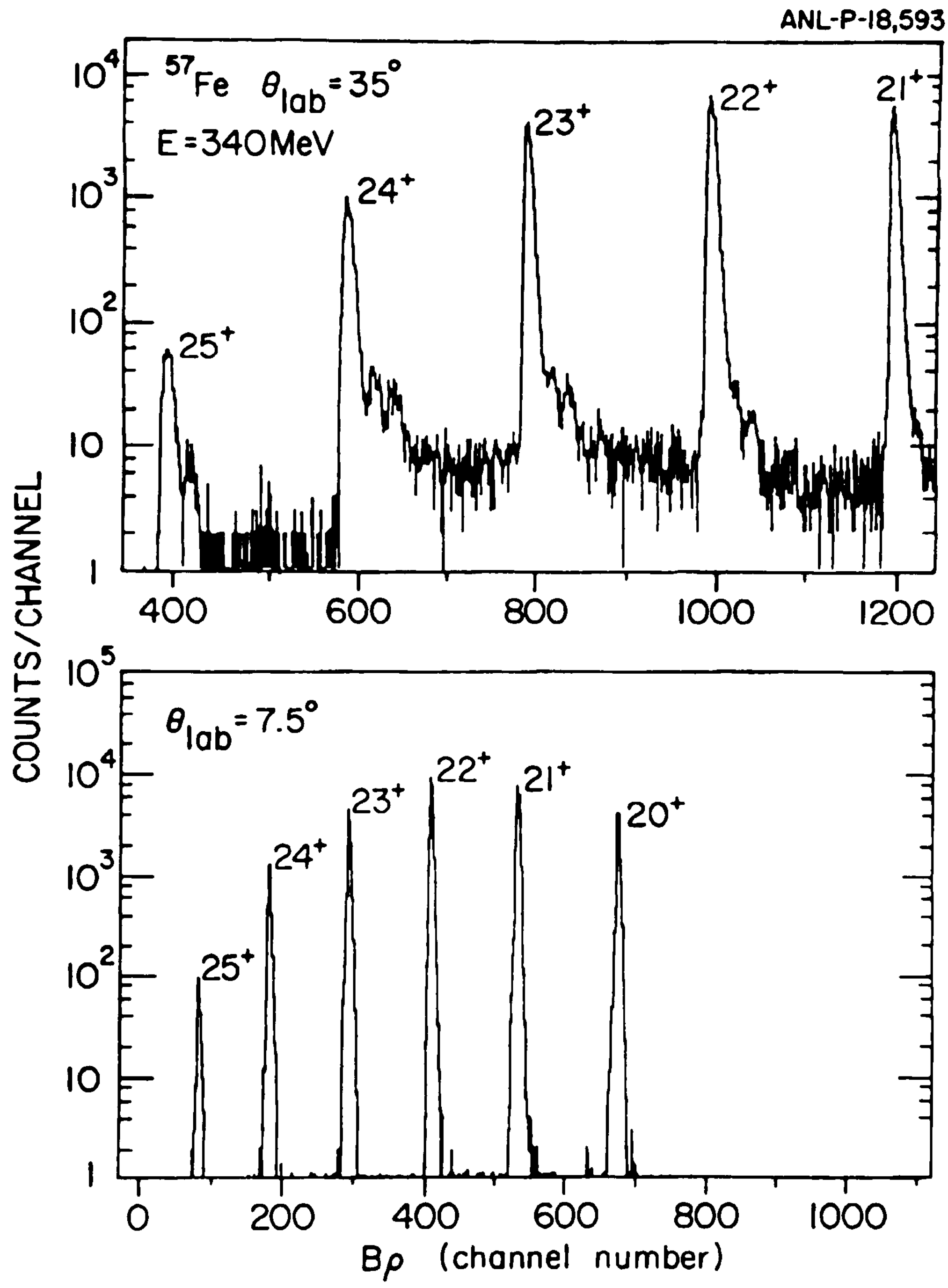

Fig. II-8. Focal-plane spectra measured at $\theta_{lab} = 35°$ (top) and $\theta_{lab} = 7.5°$ in the reaction $^{57}Fe + ^{197}Au$. The events between the stray peaks are due to charge-changing processes induced by the decay of the 14.4-keV level in ^{57}Fe (see text for details).

B. FUSION AND FISSION OF HEAVY IONS

Studies of fusion processes, both complete and incomplete fusion, represent a major component of the research performed at ATLAS.

The observation at ATLAS of neutron suppression in $^{64}Ni + ^{92}Zr$ fusion, has led to a program of measurements investigating the dependence of compound nucleus decay on the entrance channel, and the possibility of a superdeformed potential minimum arising from shell effects.

The conditions necessary for the occurrence of quasifission has been studied in great detail. Work at Argonne, revealing that the angular anisotropies of fission fragments were larger than expected, was decisive for characterizing the process. The large body of data obtained at ATLAS, from studies of the entrance channel dependence of quasifission, has contributed significantly to the existing systematics.

A series of measurements, over a significant energy range, of three different entrance channels leading to the compound nucleus ^{56}Ni, have been performed to investigate the fission process in light systems. The results indicate that the excitation functions and angular distributions of the fully-damped reaction products are consistent, at least at the lower bombarding energies, with a fusion-fission process. Studies of the energy sharing between the fragments, and the possibility of a resonance behavior in the process is being investigated in heavy-ion γ-coincidence measurements.

Studies of incomplete fusion processes, where breakup and fragmentation of the incident projectile or target lead to fusion of only parts of collision partners, have been extensively pursued. Studies at ATLAS indicate that as function of bombarding energy, different mechanisms may be responsible for these processes. From Weizmann/ATLAS measurements on heavier systems there is the suggestion that a "massive transfer" mechanism plays the dominant role at lower bombarding energies, while the ATLAS measurements on lighter systems at higher bombarding energies reveal an entrance-channel dependence which suggests that the mechanism is associated with the Fermi motion of nucleons in the interacting nuclei. The first generation of coincidence measurements which make full use of the good timing characteristics of the ATLAS beams were performed in 1986, obtaining data which hopefully will provide a much clearer picture of the reaction mechanism.

a. **Evaporation Residue Cross Sections in Fusion of $^{64}Ni + {}^{92}Zr$ and $^{12}C + {}^{144}Sm$** (R. V. F. Janssens, R. Holzmann, W. Henning, T. L. Khoo, K. T. Lesko, G. S. F. Stephans, D. C. Radford, and A. van den Berg)

As part of a study to understand the origin of neutron suppression in $^{64}Ni + {}^{92}Zr$ fusion (see Section II.C.a.), we have measured the evaporation residue cross sections. These measurements have also a direct bearing on the problem of enhanced sub-barrier fusion. Residue cross sections in fusion of $^{64}Ni + {}^{92}Zr$ and $^{12}C + {}^{144}Sm$ have been measured over a wide range of bombarding energies, including some below the Coulomb barrier. Using a technique previously developed here at ANL, the residues were separated from the beam by electrostatic deflection and detected at 4 angles including 0°. The analysis has been completed. For the $^{12}C + {}^{144}Sm$ reaction, the measured cross section agrees nicely with calculations using the empirical model of Kailas and Gupta. This result enhances the confidence one may have in the ℓ_0 values used in statistical-model calculations where neutron multiplicities were derived. In summary, all data available for the $^{12}C + {}^{144}Sm$ reaction can be accounted for consistently in the framework of the existing models.

The situation is rather different for the $^{64}Ni + {}^{92}Zr$ reaction. For energies below the barrier, enhancement of the fusion cross section with respect to the calculation is observed. Current explanations of this enhancement (e.g. coupled-channel effects or zero-point fluctuations) imply that the angular-momentum distributions will be modified. In particular, a tail towards high ℓ-values is predicted. Such a tail has been observed for 225-MeV ^{64}Ni in an experiment with the Heidelberg-Darmstadt crystal ball (see Sec. II.C.a.) where ℓ distributions were obtained. For energies above the barrier (230-240 MeV), i.e. in the range where we have reported inhibition of neutron emission, the measured fusion cross section is close to the calculated value and the ℓ_0 value derived assuming a sharp cutoff approximation is close to that deduced from the crystal-ball measurement (see Sec.II.C.a.). Finally, at the highest beam energies, the calculated fusion cross section is found to exceed the measured ER cross section. This is due to the onset of fission which is not detected in the experiment. An estimate of the fission contribution was obtained from the statistical model with the inclusion of the fission barriers recently proposed by Sierk. This contribution, when added to the measured evaporation residence cross section, allows one to reproduce the calculated fusion cross section.

In summary, these data can be combined with the crystal-ball data discussed in Sec. II.C.a. to rule out the possibility that the apparent inhibition of neutron emission is due to a high tail in the ℓ distributions. These results have now been published. The calculations of the fusion cross sections which reproduce the data for the ^{64}Ni + ^{92}Zr reaction at the barrier and below suggest strong coupling to other inelastic and transfer channels. Measurements are planned to better understand the microscopic basis for enhancement of fusion near the barrier. Experiments will focus on the fission and transfer channels to add to the systematic data on evaporation residues.

b. **Fusion of ^{78}Se + ^{78}Se and ^{82}Se + ^{82}Se** (M. Piiparinen,* M. Quader,*, R. V. F. Janssens, T. L. Khoo, W. C. Ma, R. Holzmann, M. W. Drigert,† and P. J. Daly*)

These measurements are part of a series directed towards understanding the suppression of neutron emission observed in fusion of ^{64}Ni + ^{92}Zr $\rightarrow$ ^{156}Er and not seen in fusion of ^{12}C + ^{144}Sm $\rightarrow$ ^{156}Er. The initial deformation upon fusion is larger in the former case and we have speculated that in the shape relaxation the compound nucleus may be trapped in a superdeformed potential minimum. This theoretically-predicted minimum arises from shell-structure effects and is expected to disappear in Er isotopes as the neutron number increases from 88 to 96. In the ^{78}Se + ^{78}Se $\rightarrow$ ^{156}Er and ^{82}Se + ^{82}Se $\rightarrow$ ^{164}Er fusion reactions the compound nuclei have these neutron numbers. If trapping in a superdeformed minimum is indeed the cause for neutron suppression, then this suppression should disappear in the latter case.

The channel yields have been measured in the fusion reaction of both systems in order to extract the neutron multiplicity distributions. These can be compared with results from our earlier experiments for ^{156}Er and with published results for ^{16}O + ^{148}Nd $\rightarrow$ ^{164}Er. Data analysis is now near completion and the major results can be summarized as follows: (i) in the ^{78}Se + ^{78}Se reaction, the measured neutron multiplicities, as a function of the excitation energy of the compound nucleus, follow a curve very similar to the one observed in the ^{64}Ni + ^{92}Zr reaction. Thus, the measured neutron multiplicities are lower at all energies than those calculated within the

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framework of the statistical model. (ii) for the $^{82}Se + ^{82}Se$ reaction, several problems with target impurities had limited the analysis of a first experiment. Data of better quality were recently taken with the BGO γ-ray facility. The analysis is under way.

c. **Study of Fission Fragments from the Reaction $^{32}S + ^{182}W$** (B. B. Back, J. G. Keller, B. G. Glagola, S. J. Sanders, F. Videbaek, S. Kaufman, B. D. Wilkins, D. Henderson, and R. H. Siemssen*)

This experiment is part of a program to study the effects of the entrance channel mass asymmetry on the binary reaction channels in systems leading to ^{214}Th. Reaction products from the $^{32}S + ^{182}W$ reaction were measured in an array of Si detectors over the full angular range from 20° to 160° in the laboratory system. Bombarding energies of 166, 177, 222, and 260 MeV were studied. The product masses were obtained from the combined measurement of energy and velocity of the fragments utilizing the time structure of the beam. A fraction of the coincident fragments are detected in a position-sensitive avalanche detector covering an area of 8 × 10 cm^2. Total reaction cross sections were derived from an optical-model analysis of the simultaneously measured elastic-scattering cross section. The angle-integrated fission cross section is compared with theoretical model predictions based on the proximity potential. A substantial contribution from deeply-inelastic scattering reactions was found at all energies. This component is stronger than expected on the basis of recent theoretical models based on the Extra Push concept. The fission anisotropies were analyzed in terms of the saddle-point model and they were found to be larger than predicted indicating a contribution of quasifission processes. Also the angular dependence of the average fragment mass shows indication of a weak quasifission contribution (see Fig. II-9). A manuscript describing the results of this experiment has been submitted for publication.

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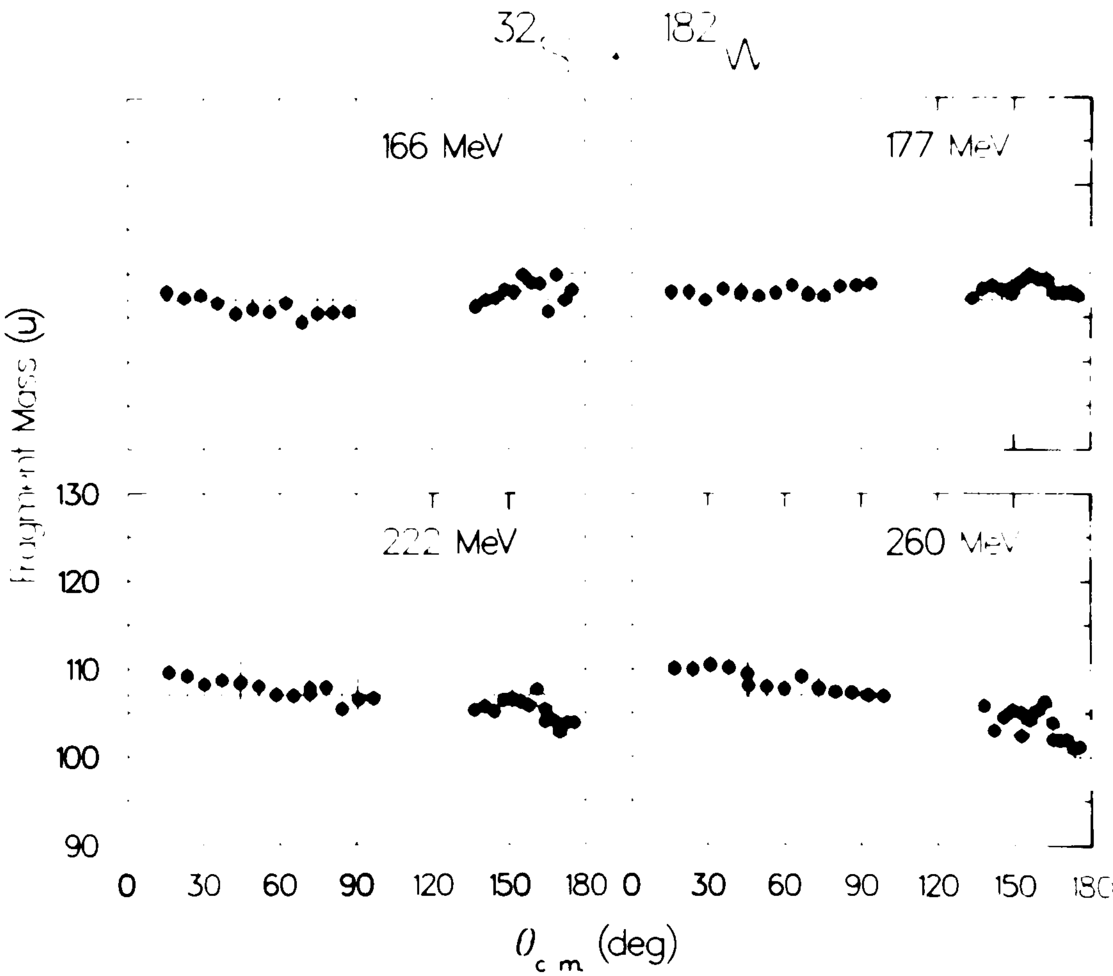

Fig. II-9. The average mass of fission-like products is shown as a function of the scattering angle at beam energies of 166, 177, 220, and 260 MeV.

d. **Experimental Study of the Reaction $^{60}Ni + ^{154}Sm$** (B. B. Back, J. G. Keller, S. J. Sanders, F. Videbaek, S. Kaufman, B. D. Wilkins, D. Henderson, and B. G. Glagola)

This experiment represents a continuation of the study of entrance-channel effects on binary reaction channels for systems leading to the possible formation of ^{214}Th. In this less-asymmetric system, as compared with the $^{32}S + ^{182}W$ reaction, we may expect non-compound nucleus reactions to contribute to the fission-like processes at a measurable level, and provide a determination of the onset of such processes as a function-of-mass asymmetry. Reaction products emitted in the forward hemisphere were measured in an array of 8 Si-detectors for beam energies of 275, 350, 400, 425 MeV. By recording time of flight of the reaction products relative to the beam timing, it is possible to determine both mass and energy of the products. From a preliminary analysis of the data it appears that a strong component of deep-inelastic scattering occurs for the two highest energies. The elastic scattering, deeply-inelastic scattering and fission-like components of the total reaction cross section will be analyzed and compared to the prediction of theoretical models.

e. **Kinematic Coincidence Studies of the $^{120}Sn + ^{94}Zr$ Reaction** (B. B. Back, F. L. H. Wolfs, J. G. Keller, B. G. Glagola, D. Henderson, S. Kaufman, F. Videbaek, S. J. Sanders, and B. D. Wilkins)

This experiment is aimed at studying binary reaction channels by using the kinematic coincidence technique. Again, the target-projectile system is chosen such that ^{214}Th would be formed in complete fusion reactions, thus extending the study to more symmetric entrance channels. The choice of a heavy beam incident onto a lighter target simplifies the experiment by focussing all the heavy reaction products into the forward hemisphere. Velocity vectors of coincident binary reaction products will be measured in two 20 × 20-cm^2 gridded parallel-plate avalanche detectors, which provide both the x-y position and the time of incidence of penetrating particles. The time of flight is obtained by utilizing the time structure of the beam. By kinematical reconstruction of each event from the measured quantities one can obtain masses, center-of-mass scattering angles and kinetic energies of the reaction products.

f. **Distribution of Reaction Strength in the ^{48}Ti + ^{166}Er Reaction** (B. B. Back, J. G. Keller, S. J. Sanders, B. G. Glagola, D. Henderson, B. D. Wilkins, and T. F. Wang)

This experiment is part of the study of entrance-channel effects of the distribution of reaction strength and general characteristics in heavy-ion collision systems leading to the ^{214}Th composite system. Reaction products from the interaction of ^{48}Ti and ^{166}Er were studied recently using beams of 220, 240, 270, and 300 MeV from the ATLAS facility. Reaction products were registered over the angular range from 7.5° to 95° in an array of 9 single Si-detectors and two Si-detector telescopes. Fragment energy and mass distributions will be obtained from the measured pulse heights and flight time over the 40-to-75-cm distance from the target to the detectors. A position sensitive avalanche counter of 8 × 10 cm^2 area was centered at 50° on the opposite side of the beam to facilitate the measurement of coincident reaction partners and allow for a test of two-body kinematics. The data obtained from this experiment, which was carried out in November 1986, are presently being analyzed.

g. **Energy Dissipation, Mass Flow and Excitation of the Tilting Mode in the ^{58}Ni + ^{208}Pb Reaction** (B. B. Back, J. G. Keller, B. G. Glagola, S. J. Sanders, F. Videbaek, B. D. Wilkins, D. Henderson, S.-M. Lee,* and M. Ogihara*)

The quasifission process is characterized by large or complete relaxation of the entrance-channel mass asymmetry without going through a step of compound nucleus formation. This process accounts for a substantial fraction of the reaction cross section in interactions between heavy targets and projectiles in the A = 35-70 mass region. The observed correlations between fragment mass and scattering angle allows for an estimation of the reaction time as shown in recent analysis of ^{238}U-induced reactions. Furthermore, the correlation between the mass drift and the reaction time indicates that the relaxation of the mass-asymmetry degree of freedom represents a damped motion with a characteristic time constant, which is independent of the temperature of the system. This points to the conclusion

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that the one-body dissipation mechanism is responsible for the energy damping in the mass-asymmetry mode.

Recently, Lützenkirchen et al. have studied the tilting mode in quasifission processes by measuring the angular distributions at angles near the beam axis. The tilting may be expressed in terms of the component K, of the total angular momentum, I, onto the internuclear axis. In the entrance channel, K is strictly zero for spinless target and projectile. If no tilting of the internuclear axis with respect to the total spin vector occurred during the process, one would observe a singularity in the cross section at $\theta = 0°$ (in the classical limit) simply because of the azimuthal angle degeneracy. The smearing of the initial singular K-distribution, which occurs during the reaction via particle exchange and transfers between the reaction partners, will manifest itself by a much-reduced peaking of the cross section near $\theta = 0°$. The only requirement for studying this tilting mode in a specific process is the presence of cross section near zero degrees. If this is the case as for many quasifission reactions, the tilting mode may be studied as a function of reaction time, mass transfer and other relevant parameters. This would give further insight into the particle exchange and transfer between the two reaction partners.

Studies of the quasifission reaction have been carried out mainly with uranium projectiles using the kinematic coincidence technique. Because nuclei in the uranium region are highly fissile a substantial fraction of the products corresponding to large mass asymmetries were lost by sequential fission of the uranium-like reaction partner.

Presently, we intend to carry out a study of the quasifission process for the $^{58}Ni + ^{208}Pb$ system. The choice of a ^{208}Pb target substantially reduces the ambiguities associated with sequential fission. Although two studies of the quasifission process with ^{208}Pb beams or targets are present in the literature, one of these experiments covers only a limited angular range, which prevents the determination of both the mass drift and the tilting mode, whereas the other experiment lacks an energy measurement of the products.

We intend to measure cross sections, angular and energy distributions of single fragments from the reaction using an array of 8 to 12 single-surface barrier detectors in addition to 1 to 2 detector telescopes in forward angles. The mass of reaction products will be determined from the time of flight of the products over the 40-60-cm distance from the target to the detectors using the time structure of the beam.

A position-sensitive Breskin-type detector with an active area of 8 × 10 cm^2 will be placed on the opposite side of the beam axis from the array of Si detectors. This will enable us to overdetermine the kinematics for two-body processes and obtain an estimate of the contribution from three-body reactions, which may not be negligible at the higher bombarding energies. Such reactions consist mainly of sequential fission of Pb-like nuclei, which are highly excited in a primary deeply-inelastic process. This experiment is presently scheduled to be carried out in August 1987.

h. **Fully-damped Yields in ^{32}S + ^{24}Mg Reactions** (S. J. Sanders, B. B. Back, C. Beck, B. K. Dichter, D. Henderson, R. V. F. Janssens, S. Kaufman, J. Keller, D. G. Kovar, T.-F. Wang, B. Wilkins, F. Videbaek, C. F. Maguire,* and F. W. Prosser, Jr.†)

We have measured the fully-damped yields from the ^{32}S + ^{24}Mg reaction at E_{cm} = 51 and 61 MeV. This work follows an earlier measurement[1] where we were able to show that many aspects of similar fully-damped yields in the ^{16}O + ^{40}Ca reaction (reaching the same ^{56}Ni compound system) can be characterized in terms of a fusion-fission mechanism. There is little known about the origin of the fully-damped yield in light systems, and both fusion-fission and deep-inelastic "orbiting" mechanisms have been suggested. We are interested in determining the overall magnitude of the process responsible for these yields, its dependence on exit-channel mass asymmetry, the energy sharing between final fragments, and, in general, whether these observables can be understood in terms of standard models of the fusion-fission mechanism. In the present measurement both reaction fragments were detected in coincidence. Full mass identification was obtained for one of the fragments using Si(surface-barrier) detectors for energy and time-of-flight determination, and position and time-of-flight information was recorded for the recoil fragment using Breskin-type avalanche counters. This configuration

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[1]S. J. Sanders et al., Phys. Rev. C 34, 1746 (1986).

enabled us to distinguish two-body reaction channels, to discriminate against contributions from light-particle target contaminants, and to obtain an estimate on the amount of light-particle evaporation from the reaction fragments. Even though the data are still being analyzed, it is already apparent that an asymmetric mass division is favored, as expected for fusion-fission in this light system, and also the general magnitude of the process is consistent with the expectations of a fusion-fission process. In Fig. II-10 we show both the observed mass distribution of the fission-like yield (open histogram) and the deduced primary mass distribution before light-particle evaporation from the reaction fragments (solid bars). Our results should lead to a better understanding of the limitations to fusion in light systems, and may help to clarify the current speculation that certain heavy-ion resonance behavior results from fusion-fission through highly-deformed, compound-nucleus configurations.

i. **Study of the $^{28}Si + ^{28}Si$ Reaction using Heavy-ion γ Coincidences**
(B. K. Dichter, S. J. Sanders, R. R. Betts, M. W. Drigert, R. Holzmann, R. V. F. Janssens, W. Kühn, T. L. Khoo, W. C. Ma, and T. F. Wang)

We have studied heavy-ion γ coincidences from $^{28}Si + ^{28}Si$ reactions leading to $^{16}O + ^{40}Ca$, $^{20}Ne + ^{36}Ar$, $^{24}Mg + ^{32}S$, and $^{28}Si + ^{28}Si$ exit channels at approximately twice the Coulomb barrier energy. The observed $^{28}Si + ^{28}Si$ inelastic scattering resonances in this energy range have been suggested to result from the decay of superdeformed (3:1 axis ratio) shape isomers in ^{56}Ni. The presence of these isomers should result in the preferential population of prolate states in the symmetric and nearly-symmetric exit channels when the scattering is on resonance. Our measurement was done at two beam energies, 115.9 and 118.8 MeV, corresponding to scattering off and on a broad ($\Gamma \sim 2$ MeV) $^{28}Si + ^{28}Si$ resonance.[1] The heavy ions were detected in two ΔE-E silicon surface-barrier detector telescopes located at ±45°. The coincident γ-rays were measured using 6 Compton-suppressed Ge detectors and 13 BGO detectors of the ANL γ-ray facility. In addition to establishing the feasibility of these particle-γ coincidence measurements — the primary goal of the present experiment -- a preliminary analysis of the BGO data indicates

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[1]R. R. Betts et al., Phys. Rev. Lett. 47, 23 (1981).

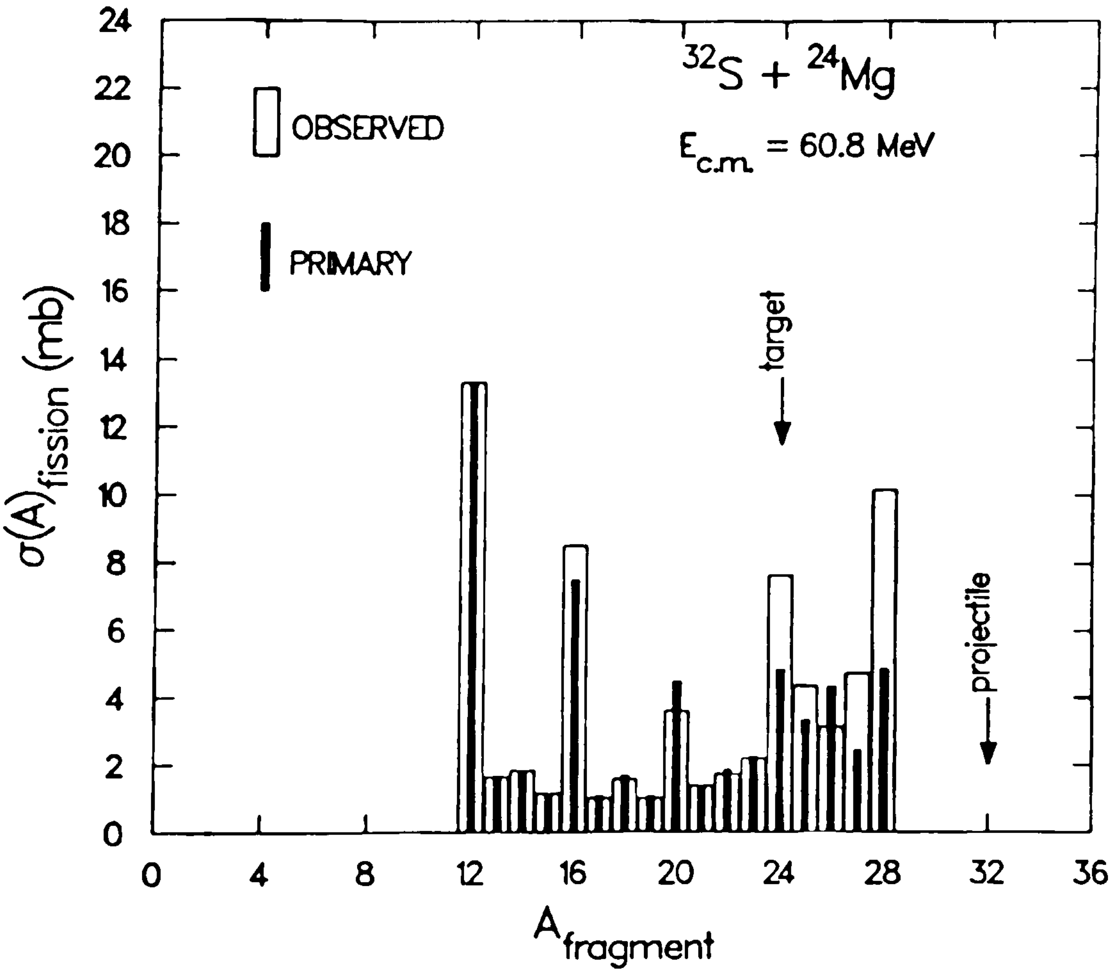

Fig. II-10. Mass distribution of the fission-like yield from the $^{32}S + ^{24}Mg$ reaction at $E_{cm} = 60.8$ MeV. The open bars indicate the observed mass yields. The solid bars indicate the deduced primary mass distribution before light-particle evaporation.

the presence of substantial strength for one or more high-energy γ transition(s) (~6-8 MeV) in the $^{28}Si + ^{28}Si$ channel. The identification of these transitions as resulting from prolate ^{28}Si configurations would be very interesting and, to identify these transitions, a follow-up experiment is planned where we will obtain high-resolution γ-ray spectra in the Ge detectors with sufficient statistics for Ge-Ge coincidences. After we identify the main γ-rays in the different exit channels, we intend to run a fine-step excitation function over several of the intermediate-width ($\Gamma \sim 150$ keV) $^{28}Si + ^{28}Si$ resonances to see if the signature of enhanced on-resonance population of prolate states is observed.

j. **Search for Shape Isomers in ^{56}Ni** (B. K. Dichter, S. J. Sanders, R. R. Betts, S. Saini, and P. D. Parker)

We have completed work on a search for evidence of shape isomerism in the ^{56}Ni system. An excitation function for the $^{40}Ca(^{16}O, ^{28}Si^*)^{28}Si^*$ reaction was measured at Yale between $74.925 < E_{lab} < 77.25$ MeV in 75-keV steps for $30° < \theta_{lab} < 60°$. Intermediate-width structures were observed in the excitation function which appear correlated with similar structure observed in elastic and inelastic $^{28}Si + ^{28}Si$ scattering yields. This strongly suggests that the process responsible for the resonances is of compound-nuclear origin. A paper on this work has recently appeared in Physical Review.

k. **Symmetric Breakup of ^{24}Mg following Inelastic Scattering** (R. R. Betts, B. R. Fulton,* S. J. Bennett,* C. A. Ogilvie,* J. S. Lilley,† D. W. Banes,† W. D. M. Rae,‡ and A. E. Smith‡)

Symmetric breakup into two ^{12}C nuclei has been observed from states at high excitation energy in ^{24}Mg excited in inelastic scattering. The experiment was performed at Daresbury with a 180-MeV ^{24}Mg beam incident on a ^{12}C target. Energies and angles of coincident ^{12}C fragments were measured in two position-sensitive detector telescopes placed at forward angles. This kinematically-complete measurement of the three-body final states allowed the

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separation of events corresponding to all three ^{12}C nuclei being emitted in their ground state. These events were then analyzed to show the excitation spectrum of the ^{24}Mg projectile excited in the first stage of the collision. This spectrum, which is shown in Fig. II-11, shows a number of prominent peaks similar to those observed in the "inverse" radiative capture of ^{12}C + ^{12}C. Similar data for ^{28}Si and ^{32}S projectiles show only very weak production of ground-state fragments in contrast to the ^{24}Mg results. It is suggested that this feature is a consequence of the structure of the projectile in its ground state.

ℓ. Fusion Evaporation Residues and the Distribution of Reaction Strength in ^{16}O + ^{40}Ca and ^{28}Si + ^{28}Si Reactions (J. Hinnefeld,* J. J. Kolata,* D. G. Kovar, C. Beck, M. F. Vineyard, D. Henderson, R. V. F. Janssens, K. T. Lesko, A. Menchaca-Rocha,† F. W. Prosser,‡ S. J. Sanders, G. S. F. Stephans, and B. Wilkins)

Previous singles measurements of the reactions ^{16}O + ^{40}Ca and ^{28}Si + ^{28}Si, which form the same compound nucleus ^{56}Ni, have revealed that at higher bombarding energies (above about 6 Mev/nucleon) the distributions of reaction strength are significantly different for the two systems. While the total reaction cross sections (determined from optical-model fits to elastic scattering) are essentially the same, the ^{28}Si + ^{28}Si total evaporation residue cross section decreases with increasing bombarding energy, whereas the ^{16}O + ^{40}Ca evaporation residue cross section remains essentially constant over the same energy range. This implies that either the fusion cross section or the evaporation-residue/fission competition in the two reactions differ significantly. Moreover, in this same energy range the velocity spectra of the evaporation residues from the ^{16}O + ^{40}Ca reaction show evidence of significant incomplete fusion contributions, while those for the ^{28}Si + ^{28}Si systems show little or no evidence of incomplete fusion. To investigate these questions, coincidence measurements between time-of-flight detectors (providing mass identification) and a large-area position-sensitive gas detector (providing Z identification) were performed for the two systems at E_{lab} = 9 MeV/nucleon to distinguish between evaporation residues and the reaction products arising from binary processes. Analysis of the results for

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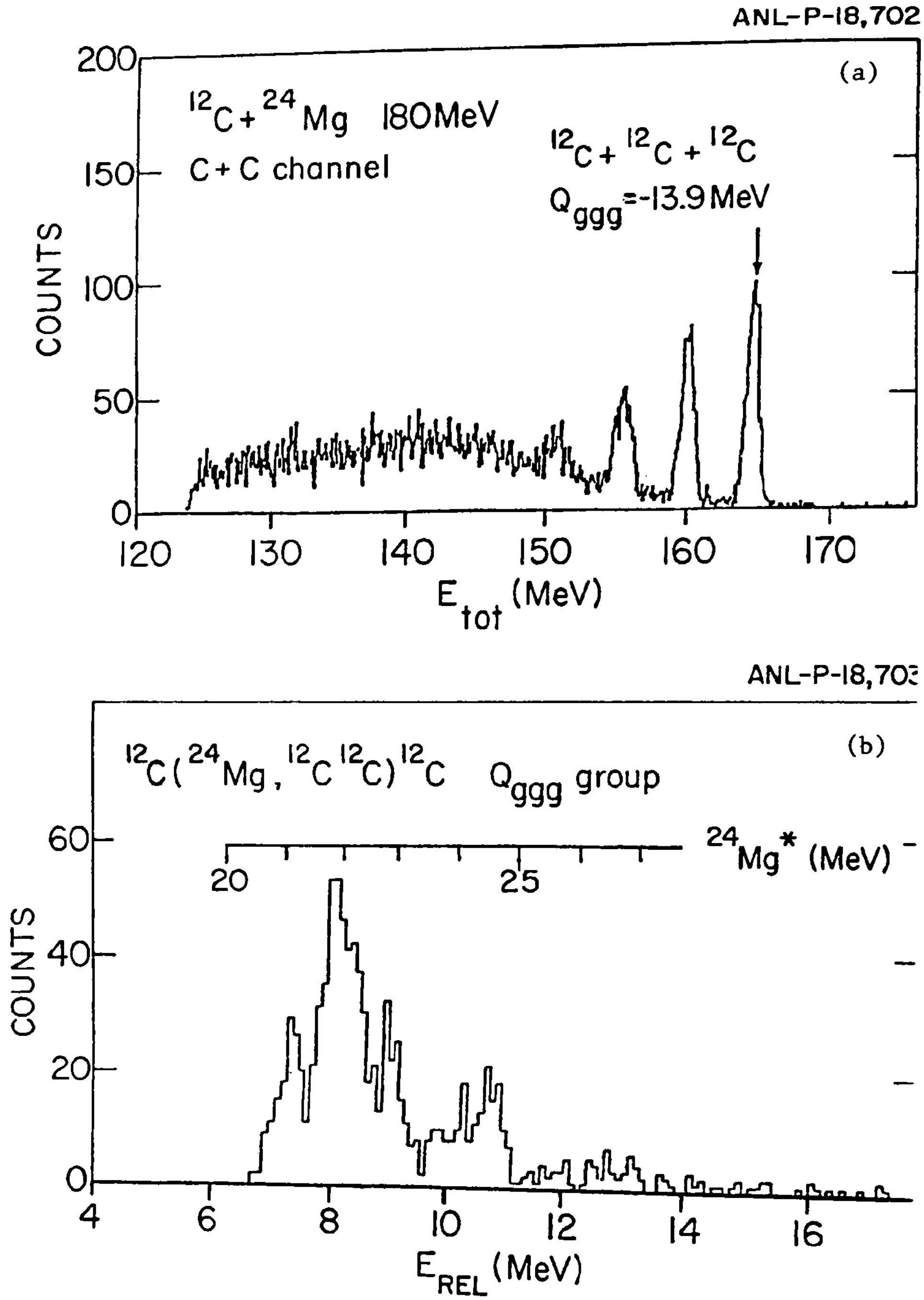

Fig. II-11. (a) Spectrum of $^{24}Mg + ^{12}C \rightarrow ^{12}C + ^{12}C + ^{12}C$ events. The peaks correspond to all three, two and one ^{12}C in the ground state, respectively. (b) Excitation energy spectrum in ^{24}Mg for events in which all three ^{12}C nuclei emerge in their ground states.

the $^{28}Si + ^{28}Si$ system is nearing completion, while the work on the $^{16}O + ^{40}Ca$ is still underway. For the $^{28}Si + ^{28}Si$ reaction, the binary fragments are found to be essentially fully damped with angular distributions which deviate from a $1/\sin\theta$ distribution at forward and back angles and a mass distribution inconsistent with symmetric fusion-fission. Attempts to interpret the behavior as a combination of a deep-inelastic component and asymmetric fission are being pursued. The yields identified as evaporation residues have velocity spectra consistent with complete fusion and a cross section in good agreement with previous singles measurements. The results will be compared to model calculations and with the results of the $^{16}O + ^{40}Ca$ reaction, when they become available.

m. **Energy and Target Dependence of Incomplete Fusion in ^{28}Si-Induced Reactions** (M. F. Vineyard,* D. G. Kovar, C. Beck, C. N. Davids, D. Henderson, R. V. F. Janssens, C. A. Maguire,† J. F. Mateja,‡ F. W. Prosser, and G. S. F. Stephans, and B. D. Wilkins)

Time-of-flight (TOF) measurements of the velocity spectra of the evaporation residues (ER) produced in the reactions of ^{28}Si with ^{12}C, ^{28}Si, and ^{40}Ca at bombarding energies of 11, 14, and 16 MeV/nucleon have been performed to study the energy and target dependence of complete and incomplete fusion processes. Previous experimental observations[1] suggest that he ratio of incomplete-to-complete fusion cross sections (extracted from the analysis of ER velocity spectra) depends on the mass asymmetry in the entrance channel and that the onset and energy dependence of incomplete fusion is governed by the center-of-mass velocity of the lighter reaction partner. However, not enough high-quality data exist to draw any firm conclusions and the results of the present study will provide additional information which should help to shed some light on the reaction mechanisms involved.

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¶Massachusetts Institute of Technology, Cambridge, MA.
[1]H. Morgenstern et al., Phys. REv. Lett. 52, 1104 (1984).

The measurements were performed in the multipurpose scattering facility at ATLAS using three TOF systems which made use of the excellent timing properties (Δt < 200 ps) of the beam. Sufficient mass resolution was obtained to resolve all of the evaporation residues produced in the reactions studied (see Fig. II-12). Velocity spectra of the individual ER masses have been created and are presently being analyzed to extract the complete and incomplete fusion cross sections.

n. **Reaction Mechanisms for $^{16}O + {}^{40}Ca$ at E_{lab} = 13.4 MeV/nucleon**

(C. Beck, D. G. Kovar, D. J. Henderson, R. V. F. Janssens, W. C. Ma, S. J. Sanders, M. Vineyard, T.-F. Wang, C. F. Maguire,* F. W. Prosser,† and G. Rosner‡)

Abnormally large evaporation residues (ER) cross sections have been reported earlier[1] for the $^{16}O + {}^{40}Ca$ reaction at high bombarding enrgies (E_{lab} > 100 MeV) in contradiction with he expectations of the Rotating Liquid Drop Model (RLDM). It was noted[2] that the ER angular distributions were too broad if compared to statistical-model calculations and interpreted as either evidence of misidentification of the ER yields due to a mixing with fusion-fission recoil products or the result of the incomplete fusion contributions (observed to be significant in this energy range[3]).

The $^{16}O + {}^{40}Ca$ reaction has been investigated using a 214-MeV ^{16}O pulsed beam from the Argonne National Laboratory ATLAS facility. Singles and coincidence measurements were performed in order to distinguish evaporation residues (arising from both complete and incomplete fusion) from binary processes (e.g., deep-inelastic collisions or fission-like reactions). The measurements were performed in the ATLAS 36" scattering chamber. An array of 5 Si surface barrier detector telescopes covering the angular range 2-52

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[1] S. E. Vigdor et al., Phys. Rev. C 20, 2147 (1979).
[2] D. G. Kovar, Proc. of Conf. on Fundamental Problems in Heavy-Ion Collisions, ed. N. Cindro, W. Greiner, and R. Caplar, World Scientific Pub., Singapore 1984, p. 1985.
[3] Y. Chan et al., Phys. Rev. C 27, 447 (1983).
[4] J. R. Birkelund and J. R. Huizenga, Ann. Rev. Nucl. Part. Sci. 33, 265 (1983); P. Frobrich, Phys. Rep. 116, 337 (1984).
[5] A. J. Sierk, Phys. Rev. C 33, 2039 (1986).

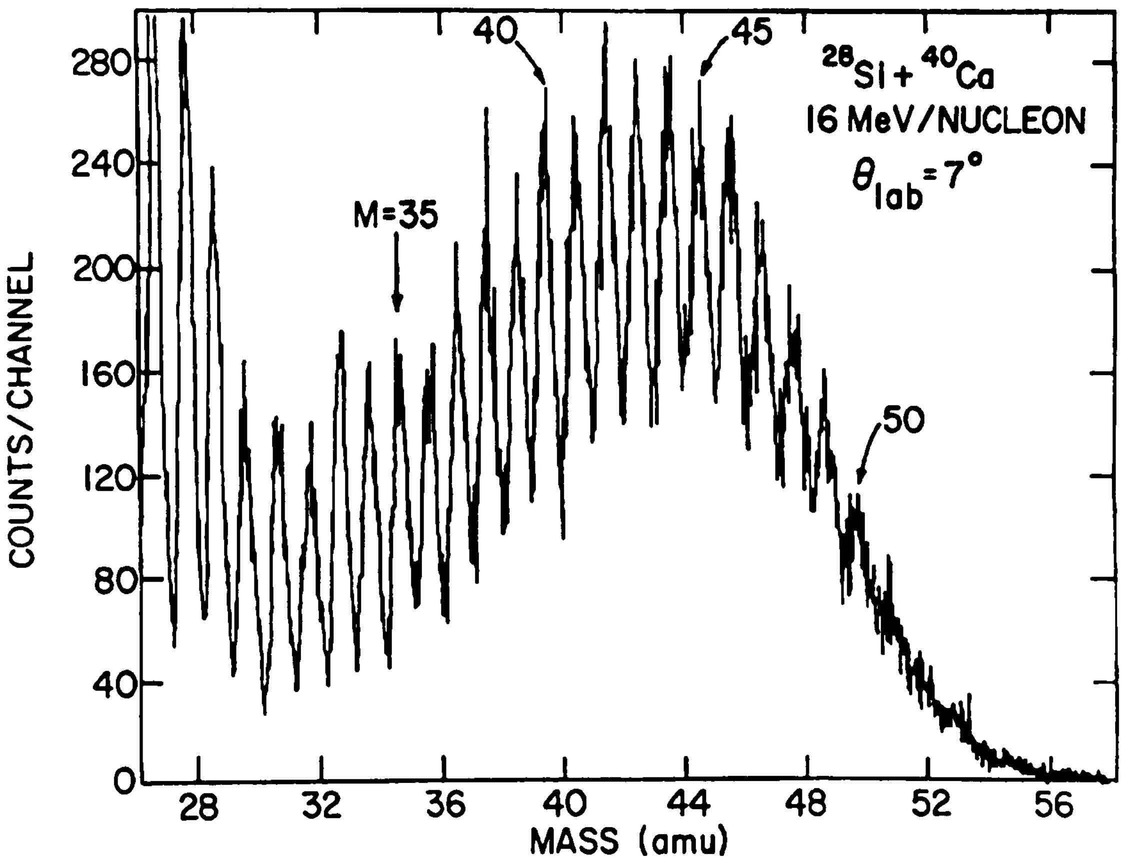

Fig. II-12. Mass spectrum of the ER-like products from the reaction of 16-Mev/nucleon ^{28}Si with ^{40}Ca measured at θ_{lab} = 7.

degrees and using beam timing ($\Delta t < 150$ ps), provided mass identification of all reaction products and allowed extraction of the velocity spectra for individual masses (Fig. II-13). Two large-area, low-pressure multi-wire avalanche counters were used in coincidence to identify the two-body processes. The light particles were detected in coincidence with the heavy fragments using 9 Si dE-E telescopes combined with 6 strip detectors and 5 NaI(Tl) crystals (using the Pulse-Shape Discrimination method).

The angular distributions for all reaction products ($6 < A < 49$) were obtained from the TOF singles velocity distributions. (The angular distributions for $32 < A < 49$ amu are shown in Fig. II-14.) Using the velocity spectra total ER cross section of 762 ± 85 mb was obtained. The fission-like cross section has been estimated to be approximately 150 mb. A careful study of the Galilean invariant velocity spectra, measured at several angles between 2-20 degrees for ER with $36 < M < 52$, reveals that the fraction of the projectile linear-momentum transfer is only 88% (in excellent agreement with Ref. 3) implying that on the average, less than 14 nucleons from the ^{16}O projectile have been captured during the fusion process. Using the Monte Carlo code LILITA to generate the velocity spectra expected for complete fusion, the total ER velocity spectra expected for complete fusion, the total ER velocity spectrum was decomposed in complete fusion and incomplete fusion contributions. Incomplete fusion was found to contribute 37%. The resulting total ER and total fusion (including the fusion-fission contributions) cross sections for complete fusion are in agreement with current dynamical fusion models (Ref. 4). Furthermore the deduced critical angular momenta for complete fusion and ER compare rather well with the calculated RLDM values obtained[5] for a vanishing fission barrier ($B_f = 0$) and a fission barrier comparable to the nucleon separation energies ($B_f = 8$ MeV) respectively. The analysis of the coincidence data is now underway and should provide further information on the pre-equilibrium light particle emission associated with the incomplete fusion processes (ER and fusion-fission).

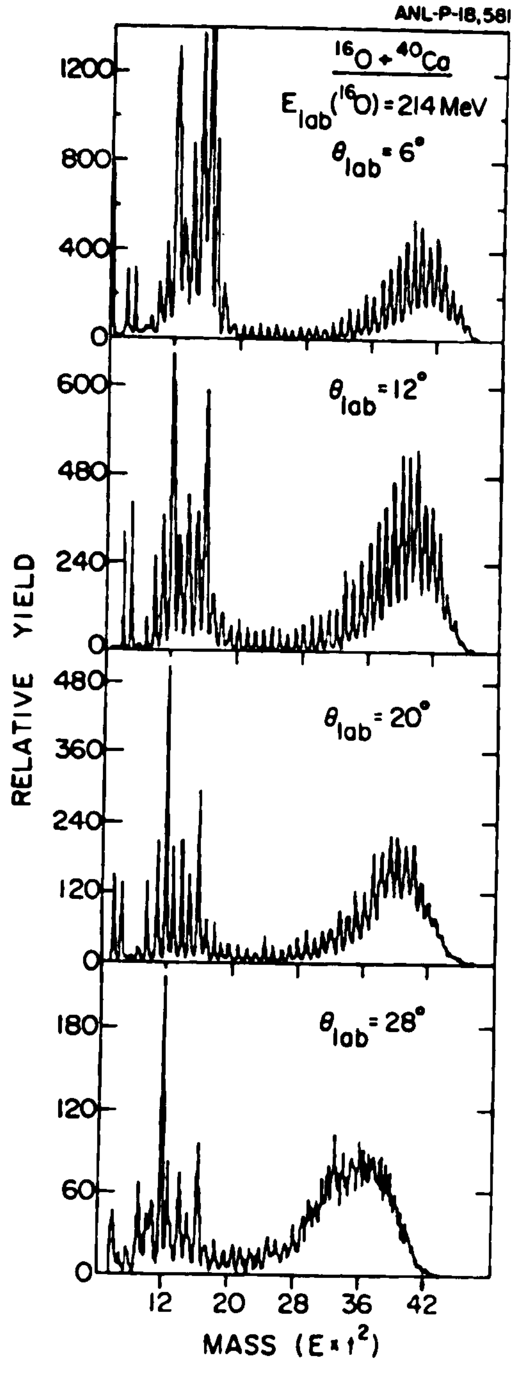

Fig. II-13. Mass resolution obtained with the various TOF detectors.

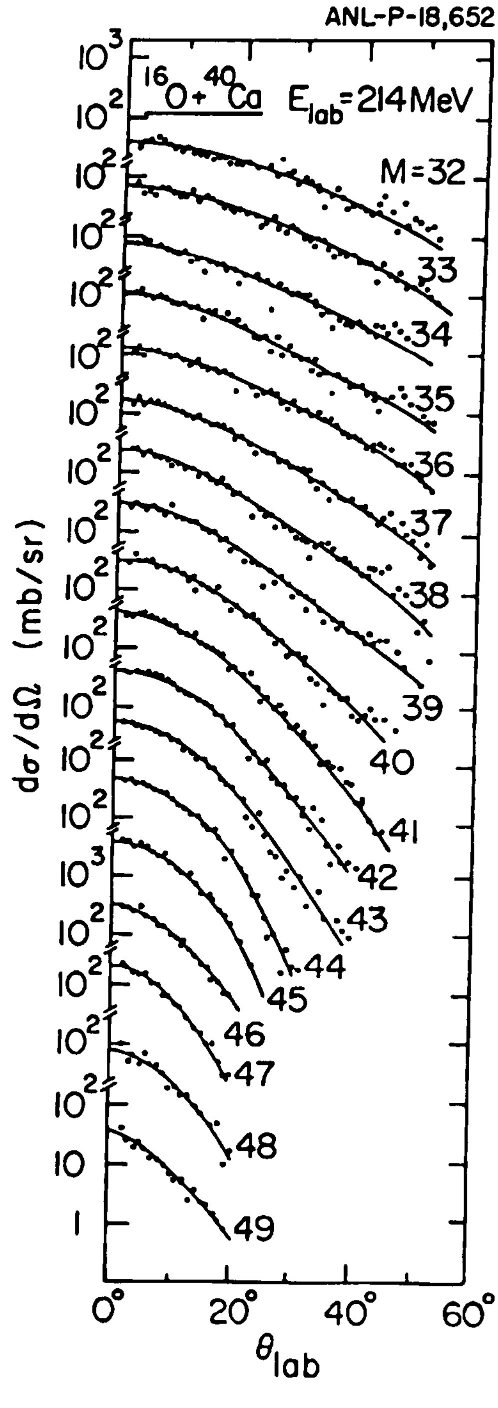

Fig. II-14. Inclusive ER angular distributions of ^{16}O + ^{40}Ca at E_{lab} = 214 MeV.

o. **Incomplete Fusion in Heavy Asymmetric Systems: $^{12}C + A(100-200)$** (I. Tserruya,* V. Steiner,* Z. Fraenkel,* J. Jacobs,* D. G. Kovar W. Henning, C. Beck, D. Henderson, B. G. Glagola, M. F. Vineyard, B. Wilkins, C. A. Maguire,† and F. W. Prosser‡)

In order to extend measurements performed at the Weizmann Institute to higher bombarding energies, cross sections for complete and incomplete fusion in collisions of ^{12}C with ^{90}Zr, ^{120}Sn, and ^{197}Au were measured in the energy range E_{lab} = 90-130 MeV using beams from ATLAS. These measurements used a large-area low-pressure multi-wire proportional counter situated at zero degrees immediately behind a small beam stopper. The detector, subtending the angular range 1.5-9.5 degrees with nearly 2π azimuthal geometry, measured the position and time-of-flight of the particles detected. The time-of-flight spectra showed evidence of a slower velocity component which was identified with incomplete fusion, and which was found to increase with increasing bombarding energy. The angular range allowed detection of ≈ 80% of the total evaporation residue yield in a single run and the extraction of an angular distribution adequate for establishing total reaction cross sections. The results of the analysis of the measurements, soon to be submitted for publication, indicate that incomplete fusion begins at energies near the Coulomb barrier and grows rapidly with bombarding energy. This behavior implies that the mechanism responsible is something like a "massive transfer" process, but coincidence measurements establishing the angular distributions and energy spectra of the pre-equilibrium light particles associated with the incomplete fusion products are necessary to draw a firm conclusion. In 1986 such a coincidence measurement was mounted and some preliminary data were obtained, but the experiment was not completed because of the problems with the accelerator. This run has been rescheduled to be run in June 1987.

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p. **Light Particle Emission in Reactions Induced at E/A > 10 MeV/Nucleon**
(P. DeYoung,* R. L. McGrath,† J. Alexander,† J. Gilfoyle,† M. Gordan,† D. G. Kovar, C. Beck, M. Vineyard, D. Bui,* D. Korteling,* and D. Bui*)

At an energy of 215 MeV the light particles (p,d,t,α) emitted from the $^{16}O + ^{27}Al$ reaction are produced via several competing reaction mechanisms. While a significant portion of the light particle cross section is the result of evaporation from a thermally equilibrated compound nucleus, the remainder of the cross section comes from mechanisms (such as hot spots) which are poorly understood. It is expected[1] that exclusive measurements such as correlations between light particles will enable one to distinguish the different components of the interaction. The $^{16}O + ^{27}Al$ reaction is of particular interest because past work by Awes et al.[2] has shown that a significant portion of the inclusive cross section is not accounted for by the statistical model.

The analysis of the $^{16}O + ^{27}Al$ system at 215 MeV is well along. We have extracted the p,d,t, and α singles cross sections, and formed the Galilean invariant cross section. The correlation functions (corrected for random coincidences) for the strongest coincident channels; p-p, p-α, and α-α have been formed. Some of these results are shown in Fig. II-15. The Galilean invariant cross section indicates that at the angle where the small angle correlations were measured, the light-particle yields are dominated by statistical emission from the compound nucleus. Thus any inferences regarding source lifetimes and sizes are assumed to apply to the compound nucleus. Detailed comparisons to theory are underway but are still at an early stage. Two theoretical approaches are being pursued. The first is a quantum-mechanical[3] approach and the second is a classical Coulomb trajectory calculation. The first correctly treats the spin statistics but ignores the

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[1]R. G. Stokstad, Comments Nucl. Part. Phys. 13, 231 (1984).
[2]T. C. Awes, S. Saini, G. Poggi, C. K. Gelbke, D. Cha, R. Legrain, and G. D. Westfall, Phys. Rev. C 25, 2361 (1982).
[3]S. E. Koonin, Phys. Rev. Lett. 70B, 43 (1977).
[4]W. G. Lynch et al., Phys. Rev. Lett. 51, 1850 (1983).
[5]P. A. DeYoung, submitted to Phys. Rev. Lett.

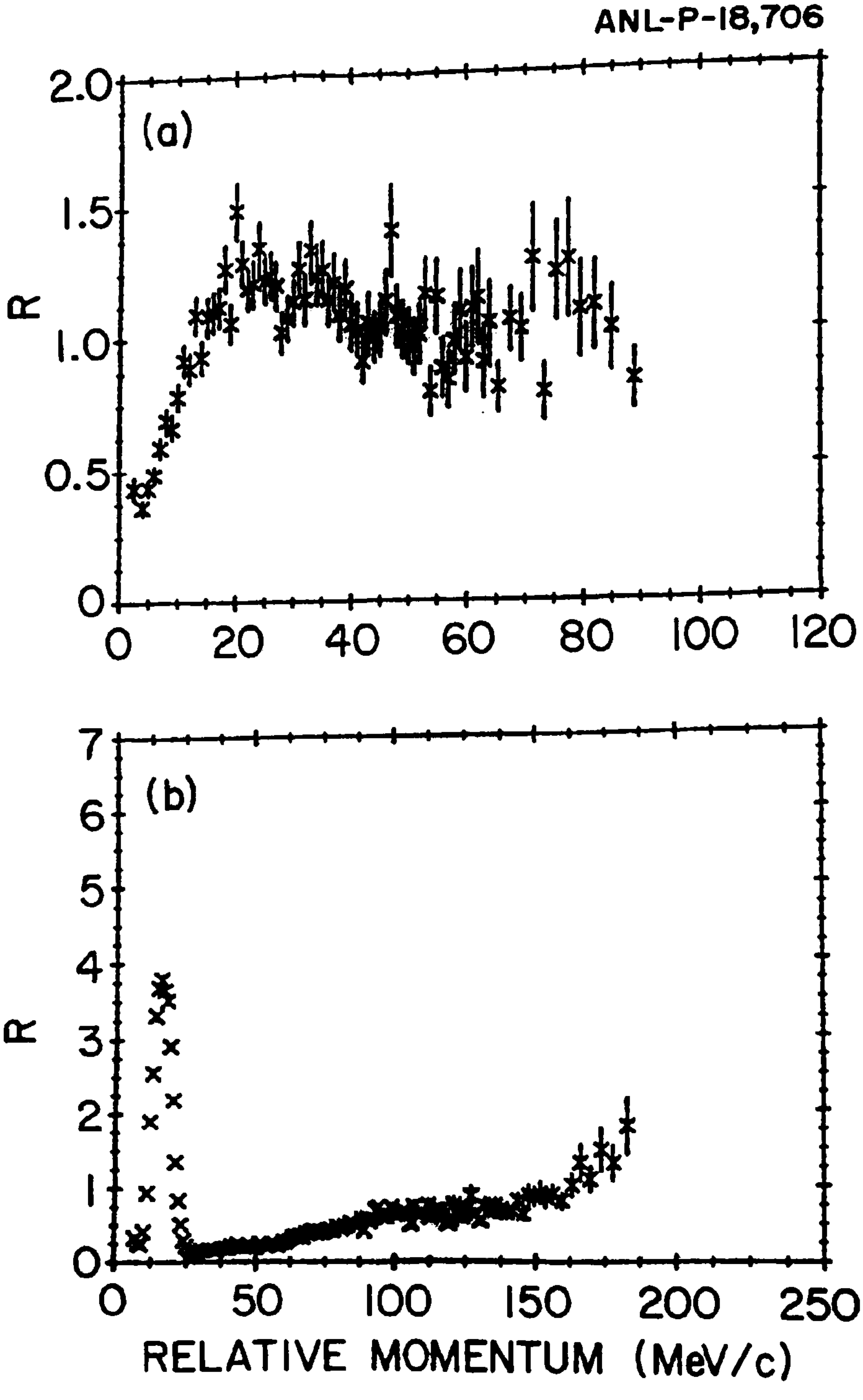

Fig. II-15. The small-angle correlation functions for the p-p and α-a system.

three-body nature of the problem while the second approach is missing the effects of the nuclear force and spin statistics. As one can see from the p-p correlation function, the source space-time extent is greater than that found for the $^{14}N + ^{197}Au$ system at 35 MeV/u (Ref. 4) because there is only the beginning of a positive correlation at 20 MeV/c. However, the source size is less than that observed[5] at 140 MeV at SUNY because the anticorrelation in the 215-MeV experiment is much deeper. A crude estimate of the lifetime (assuming a comparatively small source size) based on the correlation function would be $<10^{-21}$ seconds. This compares to a lifetime of 6×10^{-22} seconds from an extrapolation of fluctuation systematics.

Beam time for a subsequent experiment has been approved. This will allow us to measure the correlation functions at a higher energy as well as examine coincidences involving heavy fragments.

q. **Very High Energy Alpha and Nucleon Production in Heavy-ion Collisions Near Zero Degrees** (F. D. Becchetti,* J. Janecke,* P. Schulman,* S. Shaheen,* R. Stern,* A. Nadasen,† D. G. Kovar, M. Vineyard, C. Beck, and C. A. Maguire‡)

Runs at Argonne's ATLAS (500-MeV ^{32}S + Ta) and Michigan State's NSCL (480- and 600-MeV ^{16}O + Ta, Cu, and Al) have been completed during the last year. These used a single 2" × 6" BGO scintillator and 2" × 4" and 4" × 4" NaI(Tl) detectors to study light-particle production near zero degree from heavy-ion beams which stop in the target. Some data have also been obtained for thin targets. As reported last year, alpha particles out to full beam energy and nucleons to about one half beam energy are observed. The data have been analyzed using a projectile-fragmentation-plus-Fermi-motion model. The "source temperatures" extracted are very large (8-40 MeV), indicating that transfer reactions or other mechanisms might be important. Funds are being sought from NSF to purchase several large BGO detectors to permit measurements at angles larger than zero degrees and with thin targets. A short paper has been prepared for publication and an invited paper will be presented on this subject at an upcoming international conference (Gull Lake, 1987). The data will be used as part of a Ph.D. thesis project (S. Shaheen).

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r. **Incomplete Fusion in ^{16}O-induced Reactions on ^{27}Al**
(G. P. Gilfoyle,* R. L. McGrath,* J. M. Alexander,* M. S. Gordon,* G. Auger,* P. DeYoung,† D. G. Kovar, C. Beck and M. Vineyard)

The processes limiting the fusion of nuclei in heavy-ion (HI) collisions are not well understood. While certain features of incomplete fusion (ICF) like the threshold for the onset of the phenomenon have been explained[1,2] many questions remain. The shape of the differential cross section from fusion-like processes and the population of different masses at $E/A \approx 5$ MeV above the barrier are not well reproduced by calculations that have been successful at lower energies.[3-5] Even the range of impact parameters involved in the reaction mechanism is still open to questions.[5,6]

We address some of these questions for the reaction $^{16}O + ^{27}Al$ at $E_{lab}(^{16}O) = 215$ MeV. We have measured singles energy spectra over a wide angular range for both light-charged particles (LCP's) and heavier ions. Coincidences between different particle species (LCP-LCP, HI-LCP) have also been measured in several different experimental configurations. Statistical-model calculations have been performed with the computer codes LILITA[7] and PACE[8] to provide a framework to interpret these results.

Data were collected using a beam provided by the ATLAS facility of Argonne National Laboratory. Heavy fragments were detected with a three-element silicon telescope at forward angles. A pair of two-element silicon telescopes at back angles and an array of seven NaI(Tl) detectors were used for LCP detection.[9] The excellent time structure of the beam allowed time-of-flight (TOF) measurements to be made, masses in the range $4 < m < 37$ were resolved in the forward-angle HI telescope (the cross section vanished for

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†Hope College, Holland, MI.
[1] H. Morgenstern et al., Phys. Rev. Lett. 52, 1104 (1984).
[2] D. G. Kovar in Proc. of 5th Adriatic Int. Conf. on Nucl. Phys., Hvar, Croatia, Yugoslavia, ed. N. Cindro, W. Greiner, R. Caplar (World Scientific, Singapore 1984) p. 185.
[3] S. E. Vigdor et al., Phys. Rev. C 20, 2147 (1979).
[4] P. L. Gonthier et al., Nucl. Phys. A411, 289 (1983).
[5] H. Lehr et al., Proc. Symp. on Deep Inelastic and Fusion Reactions with Heavy Ions, Berlin 1979, ed. W. von Oertzen, Lecture Notes in Physics II, 117 (Springer, Berlin 1980) p. 354.
[6] H. Ikezoe et al., Nucl. Phys. A456, 298 (1986).
[7] J. Gomez del Campo et al., Phys. Rev. C 19, 2170 (1979).
[8] A. Gavron, Phys. Rev. C 21, 230 (1980).
[9] P. De Young et al., Nucl. Instrum. Methods 226, 555 (1984).

m > 37). Coincidence and singles measurements were made with the seven NaI(Tl) detectors clustered in close-packed array centered at 53.5°, the pair of two-element silicon telescopes at -150° and -170°, and the HI telescope at several negative forward angles. The results presented here are for singles events in the HI telescope.

The mass distributions in singles measured at several angles are displayed on the left side of Fig. II-16. A peak is centered near the projectile mass (m = 16) and another broad peak is at m ≈ 27 from evaporation residues (ER's). The dashed curve is the mass distribution calculated with the statistical-model code PACE for the masses populated in a complete fusion reaction. To compare the shapes the calculation has been normalized to the largest measured ER cross section at each angle. A considerable amount of observed cross section is for masses below the statistical-model prediction. One could postulate that the dominant processd at this energy is incomplete fusion where a nucleon or nucleons are emitted from the projectile with the beam velocity during the collision. A PACE calculation assuming the pre-equilibrium emission of an α (i.e. incomplete fusion) has little effect on the predicted mass distribution because the composite nucleus has less excitation energy and thus evaporates fewer particles.

The differential cross section of the ER's is shown in Fig. II-17. The curve represents the statistical-model prediction. Again the agreement is poor, the evaporation residues are kicked out to much larger angles than the calculation can account for. The same behavior is seen for the angular distributions for each individual residue mass.

The velocity spectra in singles are shown in Figs. II-18 and II-19. For masses greater than 28 the spectra peak at a velocity of 1.6 cm/ns, well below the compound nucleus velocity of 1.9 cm/ns (marked by the dashed line), implying that incompletee momentum transfer has occurred. In fact, this shift (fron 1.9 cm/ns to 1.6 cm/ns) can be accounted for by the emission, on average, of 3.7 nucleons with the beam velocity. Indeed the incomplete-fusion statistical-model calculation described above did populate masses in this region. For A < 28 the situation is more complicated. The spectra get considerably broader in a smooth fashion above $v_{ER} \approx 1.5$ cm/ns as one might expect if a fusion-like process populates them. However, there is also considerable production at low velocity. This low velocity component

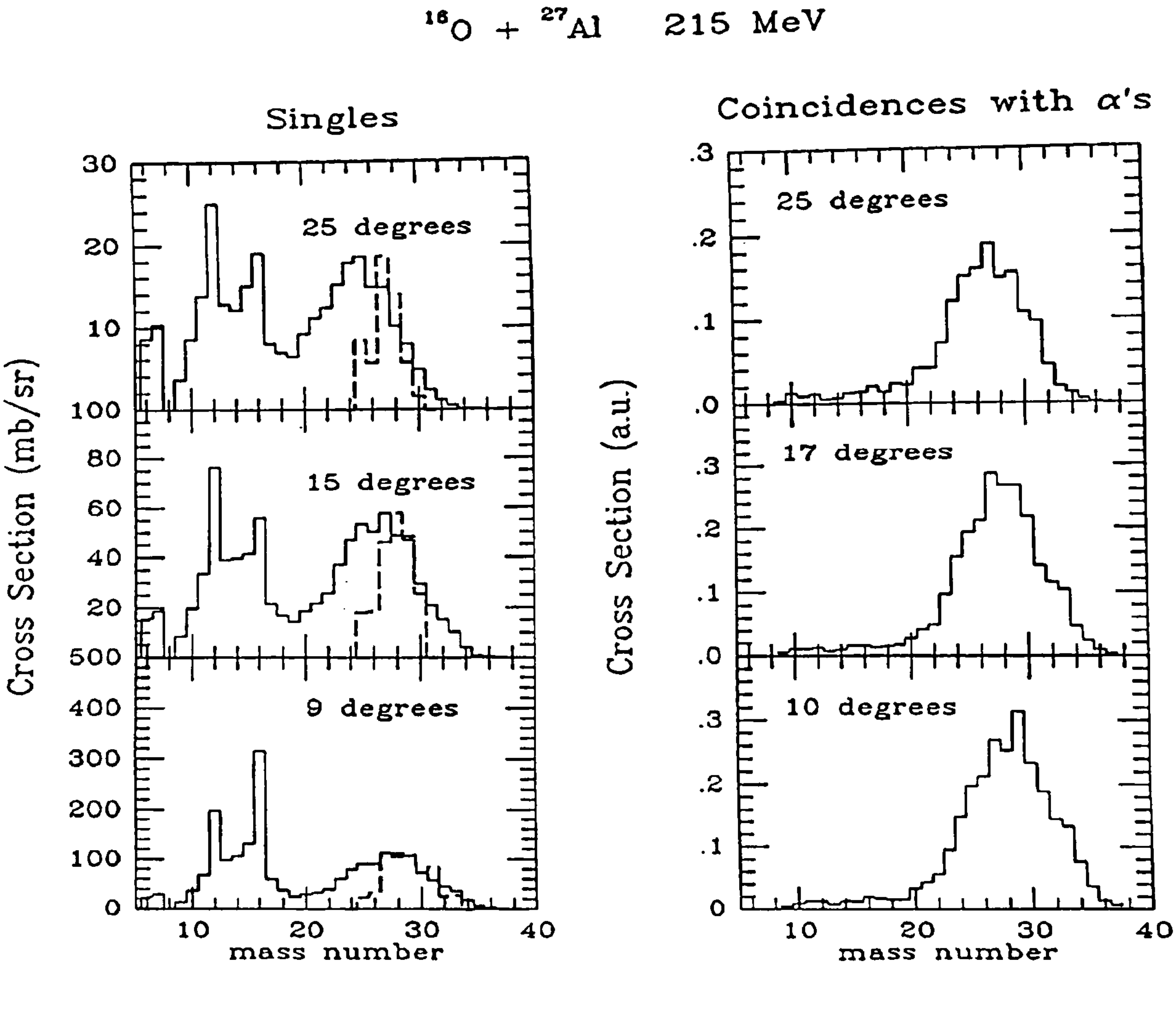

Fig. II-16. Mass distributions observed at θ_{lab} = 9°, 15°, and 25° in singles and in coincidence with alpha particles detected in a hodoscope located at 53°.

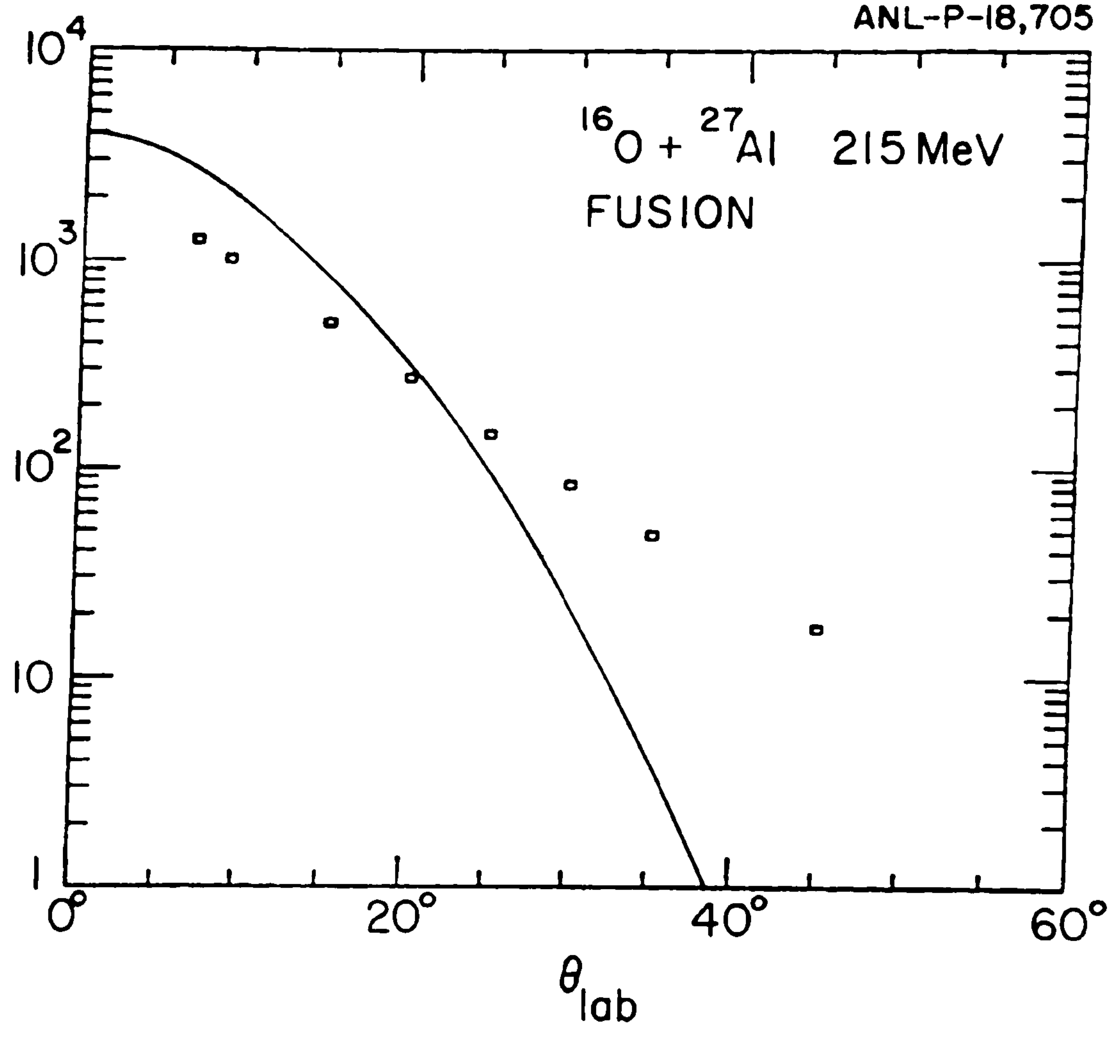

Fig. II-17. Differential cross section measured for evaporation residues.

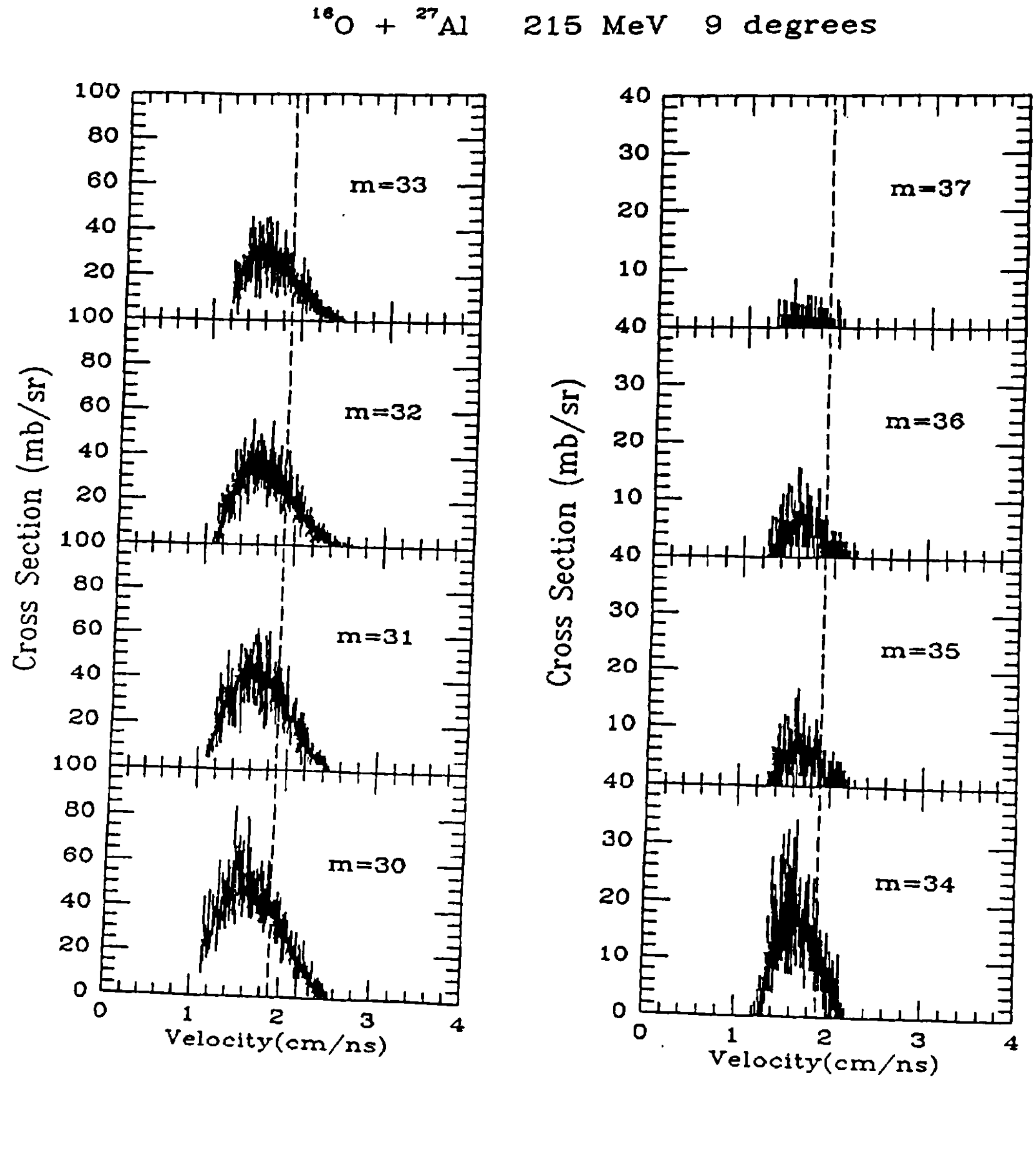

Fig. II-18. Velocity spectra of reaction products 30 < A < 37 observed at θ_{lab} = 9 degrees. Dashed line indicates expected centroid velocity for evaporation residues from complete fusion.

becomes prominent near the target mass with a velocity consistent with a deep inelastic process in which a projectile-like particle is emitted in the forward direction with the Coulomb energy and the remaining target-like nucleus recoils.

Tentative conclusions can be drawn from these results. For $m > 28$ the reaction mechanism is dominated by the pre-equilibrium emission of an α particle (or $\approx$ 4 nucleons) at the beam velocity followed by fusion of the remainder of the projectile with the target. At lower masses a fusion-like component remains, but the spectra are complicated by the presence of an additional process. The width of the fusion angular distribution is too broad to be explained by a standard evaporation calculation and remains a mystery.

The right side of Fig. II-16 shows the mass distribution at several angles in coincidence with an α particle detected in the NaI(Tl) hodoscope centered at 53.5°. The centroid and width of the ER peak are unchanged implying the same reaction process populates all the masses in the peak. The interpretatin of the lack of cross section near the projectile mass is complicated by kinematic effects so calculations are proceeding to simulate events associated with an evaporative process or a deep-inelastic reaction mechanism. Another experiment is scheduled at ATLAS to investigate coincidences between forward-angle LCP's (in- and out-of-plane) and heavy fragments and also coincidences between two HI's.

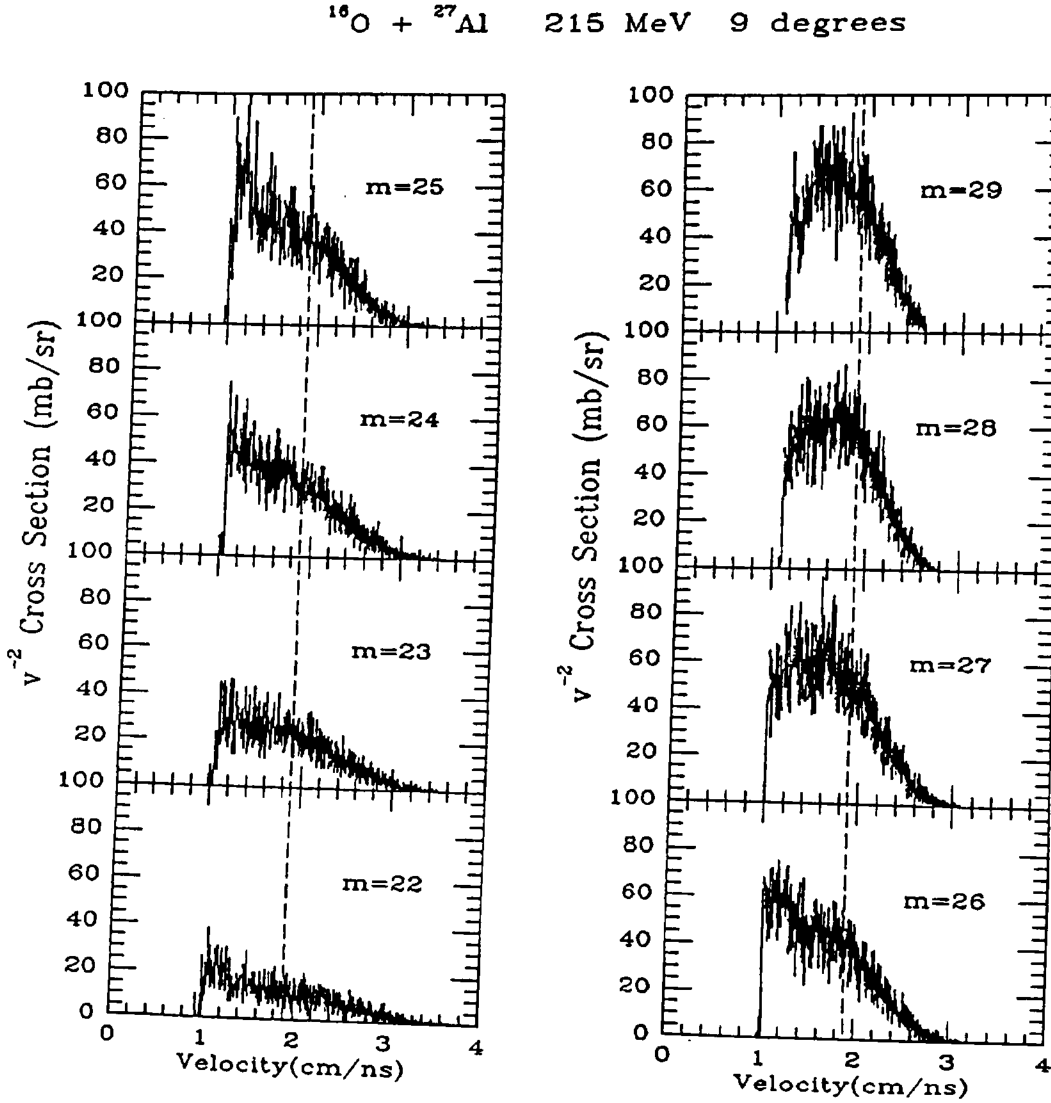

Fig. II-19. Velocity spectra of reaction products 22 < A < 29 observed at θ_{lab} = 9 degrees. Dashed line indicates expected centroid velocity for evaporation residues from complete fusion.

C. HIGH ANGULAR MOMENTUM STATES IN NUCLEI

The research program focusses on three major areas: (a) research on reflection asymmetric nuclear shapes, (b) studies of nuclear structure at very high spins on and above the yrast line and (c) investigations of the properties of the compound nucleus decay.

All of these projects have benefited immensely from the Argonne-Notre Dame BGO γ-ray facility. Phase I of the construction of this detector system, (8 Compton-Suppressed Ge (CSG) detectors and a multiplicity filter of 14 hexagonal BGO elements) has been heavily used in 1986, not only with heavy-ion beams from the accelerator but also with radioactive sources. Phase II of this construction project is under way. All additional BGO elements required to complete the sum/multiplicity spectrometer and four more CSG's are currently on order.

Research on octupole shapes focussed on the neutron-rich barium isotopes where such deformation had been predicted. These very neutron-rich nuclei are not accessible with the usually in-beam techniques. However, partial decay schemes for the nuclei ^{142,144,146}Ba have now been determined by the study of γ-γ coincidences (measured with the CSG's) from ^{252}Cf fission fragments. Interlaced positive- and negative-parity levels connected by fast electric dipole transitions were observed in ^{144,146}Ba. The data have been interpreted in terms of reflection-asymmetric shapes. The study of γ-decay of fission fragments should develop into a very powerful tool for spectroscopy studies far from stability.

Research on nuclear structure at very high spin concentrated mainly on the nuclei ^{154}Dy and ^{147,148}Gd. In ^{154}Dy the yrast line is collective at low spins, manifests backbending due to rotational alignment, and for I $\gtrsim$ 32 $\hbar$ exhibits the onset of the oblate coupling scheme. For I $\gtrsim$ 38 $\hbar$ there is a return to collective character. In ^{148}Gd, the level scheme was extended up to 44 $\hbar$ and features irregularly-spaced yrast excitations of the aligned particle type. For I $\gtrsim$ 38 $\hbar$ there is an unexpected appearance of a new collective structure with a very large effective moment of intertia.

Information on the properties of the compound nucleus decay came from two types of investigations. The γ-decay of a compound nucleus after particle-evaporation was studied by measuring the total γ-ray spectrum with the CSG's. We have established that when the yrast states are of single-particle character, a region up to 1-2 MeV above the yrast line also has similar character. At higher energy and spin, these single-particle states give way to collective E2 structures. The time evolution of the γ-deexcitation cascade has been firmly established. A simple model can account for <u>all</u> observed features (spectral shapes, multipolarities, multiplicities and lifetimes).

Our investigations of the stage preceding γ-ray emission have focussed on the origin of the suppression of neutron emission seen in some heavy-ion-induced fusion reactions. We have evidence for an entrance-channel dependence in the compound-nucleus decay. It appears that the initial stage of the decay could be influenced by shell-structure effects.

Several projects are joint ventures with outside user groups from Notre Dame, Purdue, Chalk River, Copenhagen, GSI, Heidelberg, Giessen, Strasbourg and Tennessee Technical University.

a. **Entrance-channel Dependence in the Decay of ^{156}Er** (T. L. Khoo, R. V. F. Janssens, W. Kühn,* V. Metag,* A. Ruckelshausen,*, D. Habs,† H. Gröger,† R. Repnow,† S. Hlavac‡ R. Simon,‡ G. Duchene ,§ R. Freeman.§ B. Haas,§ and F. Haas§)

We have previously observed that in fusion of ^{64}Ni and ^{92}Zr there is a suppression of neutron emission, whereas in fusion of ^{12}C and ^{144}Sm into the same compound nucleus the observed neutron multiplicity distribution is close to that expected. Possible explanations for the suppression in terms of anomalously energetic neutrons, unusually large gamma-decay widths or an unknown yrast line have been ruled out. Measurements of the ℓ-distribution of the compound nucleus in the ^{64}Ni-induced reaction have ruled out the possiblity that the explanation lies in a tail which extends to very high ℓ-values.

The measurements of ℓ-distributions have been performed with the Darmstadt-Heidelberg crystal ball at the Heidelberg tandem-linac accelerator. Care has been taken to correct for the detector response, to determine the average spin removed per photon, and to convert from multiplicity to spin. The ℓ-distributions associated with individual channels have been determined in both the ^{12}C- and ^{64}Ni-induced reactions which lead to ^{156}Er* at the same compound-nucleus excitation energy [Fig. II-20(a)]. It was therefore possible to examine the decay of the compound nucleus for the same E and I in the two reactions.

If the Bohr hypothesis is applied there should be no memory of the entrance channel during particle decay and hence no entrance-channel dependence on the reaction. Instead we find such a dependence. The ratio of cross sections corresponding to emission of 2 and 3 neutrons, $\sigma(2n)/\sigma(3n)$ is almost identical at low spins (I ~ 15) but becomes significantly larger at high spin for the ^{64}Ni-induced reaction [Fig. II-20(b)]. Thus there is memory of the entrance channel during particle evaporation. This result would be expected if, during relaxation from the initially deformed shape, the compound nucleus were to be trapped in a superdeformed secondary potential minimum.

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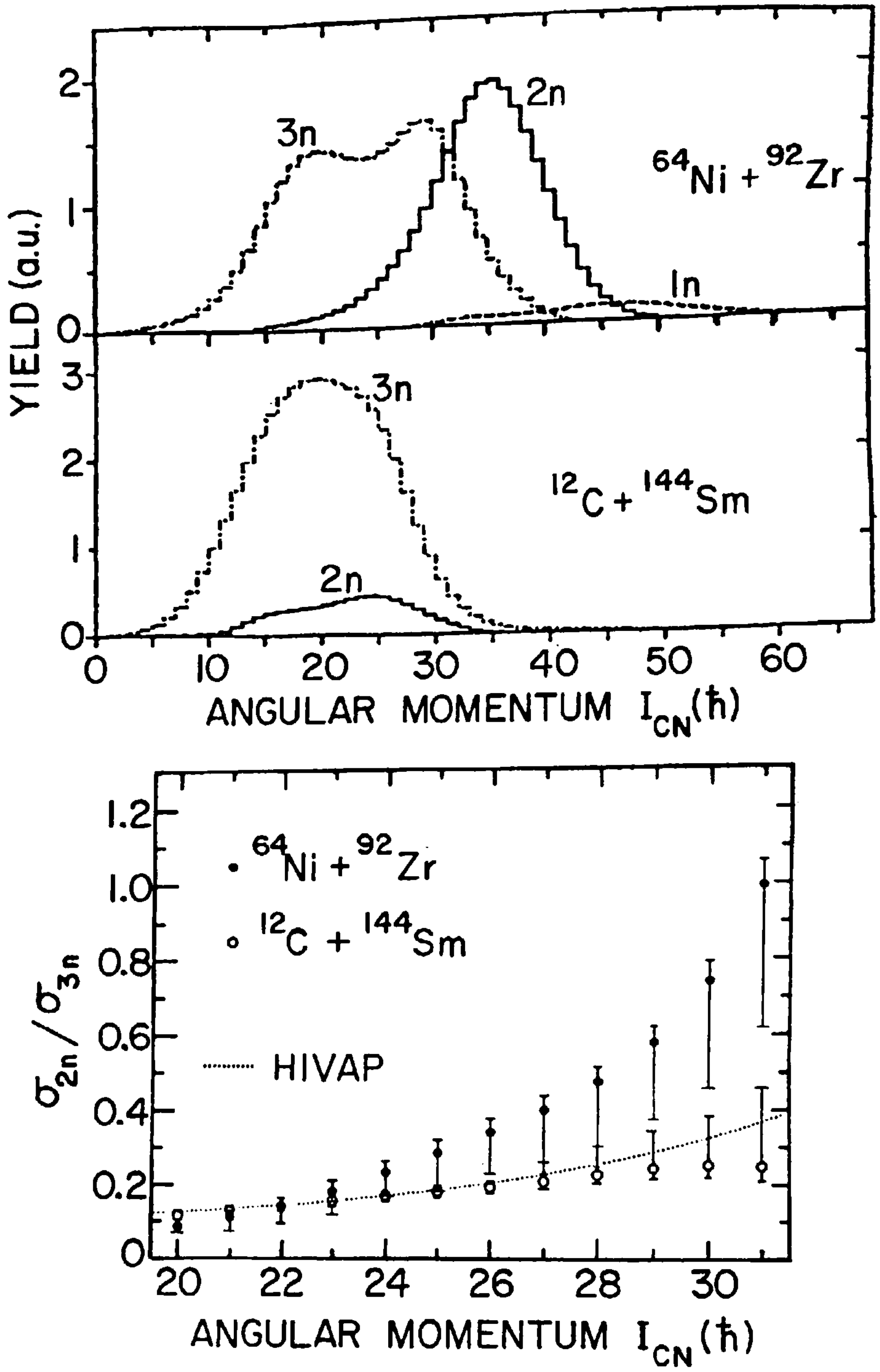

Fig. II-20. (a) CN spin distributions for the channels corresponding to 2- and 3-neutron emission following the $^{64}Ni + ^{92}Zr$ and $^{12}C + ^{144}Sm$ reactions at E^*=47 MeV. The uncertainty in spin is ±10%. (b) Ratio of σ_{2n}/σ_{3n} for the indicated reactions as function of CN spin. The errors include effects of increasing the measured spins of only the 2n channel by 10%, to simulate the worst case situation. For $\ell \gtrsim 26$ it appears that neutron emission is dependent on the entrance channel. The dotted line, from a statistical calcuation using the code HIVAP, agrees with the ratio from the C + Sm channel but not with that from the Ni + Zr channel.

The initial deformation in the C-induced reaction is not sufficiently large to enable the population of the superdeformed shape. These results have been published this year.

It should also be pointed out that the spin distributions reported here and evaporation residue cross sections [σ(ER)] discussed in Sec. II.B.a. provide two data sets which are not only complementary, but also allow a cross check between the sets. In particular, the critical angular momenta ℓ_0 derived from σ(ER) (assuming the expressions given in the code CASCADE for the transmission coefficients and for the cross sections) and the values derived from the multiplicity distributions can be compared. From a compound-nucleus excitation energy of 47 MeV, data are available to compare σ_ℓ derived by the two methods for the two reactions under discussion. For the C case there is agreement within the errors, with $\ell_0 = 27 \pm 3$ $\hbar$ obtained with both methods. For the ^{64}Ni case there is agreement within the errors: ℓ_0 values of 38 ± 4 and 46 ± 4 $\hbar$ are derived from the spin distribution and σ(ER) measurements, respectively.

All of our experimental data to date (ℓ-distributions, neutron multiplicity distributions, their dependence on neutron number and entrance channel and evaporation-residue cross sections) are all consistent with a picture of trapping in a superdeformed well during compound-nucleus decay.

b. **Measurement of the Nuclear Level Density at High Spins**
(R. V. F. Janssens, T. L. Khoo, S. Henss,* A. Ruckelshausen,* R. D. Fischer,* W. Kühn* V. Metag,* R. Novotny,* D. Habs,† B. Haas,§ and F. Haas§)

In the same experiment discussed above (section II.C.a.), the level density in ^{155}Er has been measured at an average spin of 52 $\hbar$ in the excitation-energy range of 27 to 37 MeV from an analysis of the neutron spectrum in the reaction ^{92}Zr(^{64}Ni,1n)^{155}Er. The experimental approach is based on the measurement of n-spectra in coincidence with a 4π multi-element γ-detector system which provides exit channel and spin selection. Ambiguities

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in the determination of level densities usually encountered in the analysis of particle-evaporation spectra are thereby avoided. Using the usual Fermi gas approximation for level densities, a level-density parameter $a = A/(8.8 \pm 1.3)$ MeV^{-1} was deduced.

c. **Measurement of the Shape of the Neutron Spectrum and of the Total γ-ray Spectrum in the Reaction $^{64}Ni + ^{92}Zr$** (J. J. Kolata,* L. Goettig,* B. Dichter, M. W. Drigert,* R. Holzmann, R. V. F. Janssens, T. L. Khoo, W. Kühn, W. C. Ma, M. Quader,† and R. M. Ronningen‡)

As discussed elsewhere in this report, we have strong indications from a series of experiments that the time scale for shape relaxation following fusion may be affected by shell effects and may, in this case, be 3-4 orders of magnitude slower than normally expected. The experimental findings to date are: a) the average n-multiplicity in fusion of $^{64}Ni + ^{92}Zr$ is ~0.4 smaller than that observed in fusion of $^{12}C + ^{144}Sm$ for the same excitation energy in the compound nucleus ^{156}Er; b) this statement is also true for individual partial waves $\ell > 20\ \hbar$; c) the suppression of n-emission is not due to the uncertainties regarding the location of yrast line, the γ-strength function, the neutron kinetic energy or the ℓ-distributions; d) where there is suppression of neutron emission the excess energy is removed by γ-rays, as directly reflected in the measured sum energy. An experiment has been performed to measure the low-energy neutron spectrum for specific channels and the spectrum of γ rays removing the excess energy described in point d). Previous work has shown that the spectral shape of low-energy neutrons is particularly sensitive to the location of the yrast line. The spectrum of the γ rays which remove the extra energy can be extracted by measuring and comparing the total γ spectra for the different evaporation residues using the BGO Compton-Suppressed Spectrometers (CSS), in conjunction with the unfolding techniques developed at the Laboratory.

A preliminary measurement was performed in December 1986. Using the $^{64}Ni + ^{92}Zr$ reaction at 239 MeV, n-γ (NE213-CSG) and γ-γ (CSG-CSG) coincidences were recorded. This was done with a 1-mg/cm^2 target (which is

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too thick for the experiment). Preliminary analysis shows that the background due to scattered neutrons in the 4 NE213 detectors (placed at 5°, 35°, 55° and 90°) never exceeds 25% for the energies of interest. The final measurement will take place during 1987.

d. **Charged-Particle Gamma-ray Coincidences as a Probe of Nuclear Structure at High Spin** (R. R. Betts, B. Dichter, M. Drigert,† R. Holzmann, R. V. F. Janssens, W. Kühn,* T. L. Khoo, W. C. Ma, and S. J. Sanders)

The energy spectra and correlations of particles emitted by hot compound nuclei potentially contain significant information on the properties of the emitting system. The spectra of charged particles are of particular interest in that they are sensitive to the shape of the emitting system through the dependence of the Coulomb barrier on the orientation of the nucleus relative to the direction of emission.

An experiment to test these ideas has been performed using light-particle detector telescopes operated in coincidence with elements of the BGO-CSS array. Spectra of alpha particles and protons in coincidence with gamma rays emitted following fusion of ^{64}Ni + ^{92}Zr have been obtained. This system is of particular interest in that evidence from neutron multiplicities in the same reaction suggests that the compound nucleus (^{156}Er) may be superdeformed at high spin.

Figure II-21 shows center-of-mass energy spectra of alpha prticles measured at angles of 0° and 90°, obtained in coincidence with gamma rays from ^{150}Dy and ^{151}Dy, corresponding to the α,1n and α,2n evaporation from the ^{156}Er compound nucleus. The most apparent feature of these spectra is that the average alpha-particle energies at 0° are lower than those at 90° by approximately 2 MeV. Less noticable is a shift between the alpha particles emitted at the same angle in coincidence with ^{151}Dy and ^{150}Dy gamma rays. Proton spectra obtained in coincidence with ^{153}Ho gamma rays show a similar shift with observation angle which is a factor of two smaller than for the alphas. Finally, the observed yields of alpha particles correspond to large (3-5) anisotropies which are different in the cases of ^{150}Dy and ^{151}Dy.

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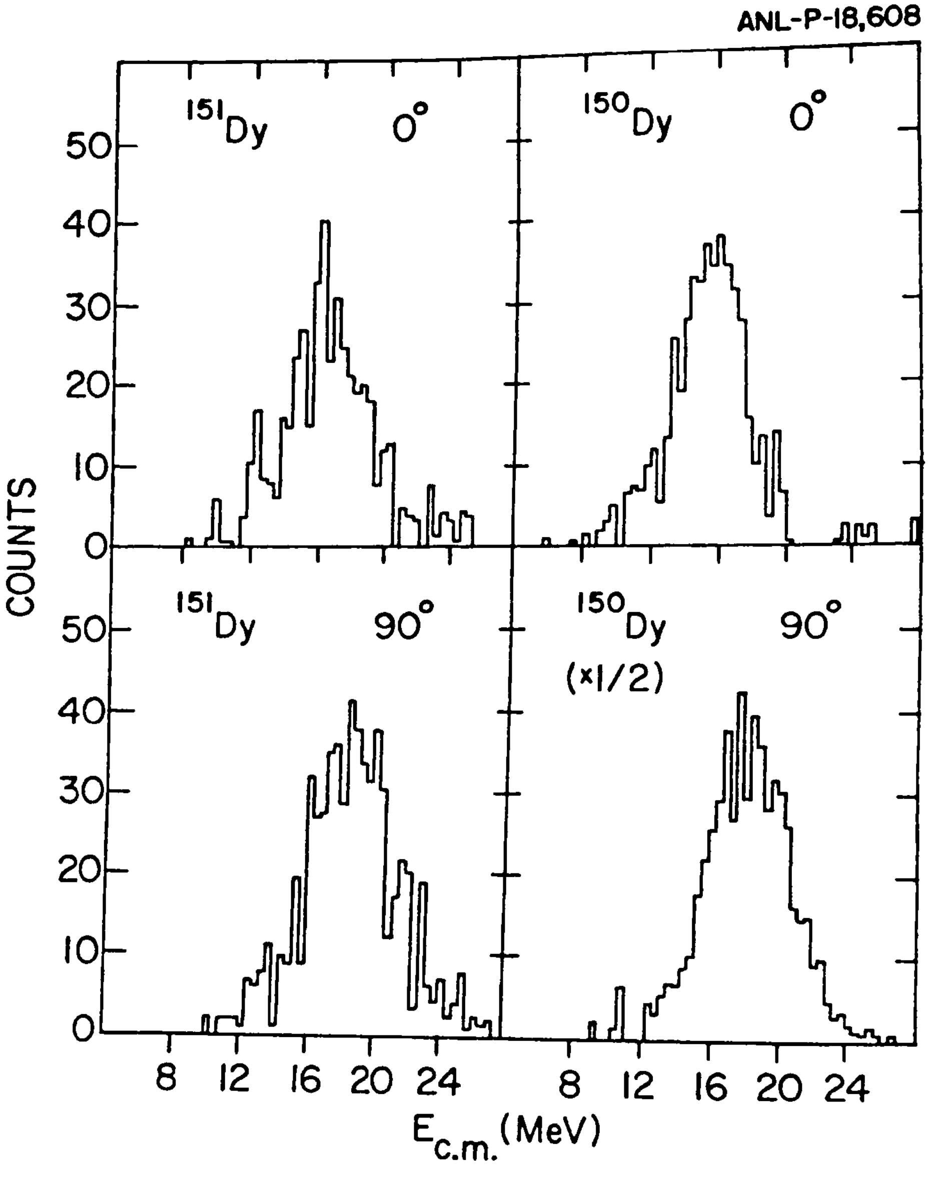

Fig. II-21. Center-of-mass energy spectra for α particles at 0° and 90° observed at coincidence with γ rays from ^{150}Dy and ^{151}Dy.

The origin of these effects is not understood in a detailed way at present. It is likely, however, that the observed difference in the alpha-particle spectra and yields reflect in some way the shape of the emitting system. Calculations of the average static barrier for the emission of alpha particles from a deformed rotating nucleus as seen by detectors at the two observation angles do indeed show a lowering of the barrier at 0 degrees relative to that at 90 degrees. In fact, to reproduce the observed shift of 2 MeV, a static quadrupole deformation of 0.6 is required. The inclusion of angular momentum of the emitted particle in this calculation serves only to reduce the difference between the energies at the two angles and the quantitative connection between our observations and the properties of the emitting nucleus is therefore unclear at the present time. Nevertheless, we believe that these data, together with a more sophisticated model analysis, will possibly provide unique new information on nuclear shapes at high spin.

e. <u>High-spin Structure in ^{153,154}Dy</u> (W. C. Ma, M. Quader,* I. Ahmad, B. Dichter, H. Emling, R. Holzmann, R. V. F. Janssens, T. L. Khoo, M. W. Drigert,† U. Garg,† P. J. Daly,* Z. Grabowski,* M. Piiparinen,* and W. Trzaska*)

The variation of nuclear shape with increasing spin is currently one of the main themes in the study of high-spin states. The transitional nuclei with N = 86-90 have been the subject of extensive experimental and theoretical studies over recent years. ^{154}Dy studied in this laboratory was the first heavy nucleus in which a transition from prolate-to-oblate shape was found. Thus this N = 88 nucleus has features characteristic of both the prolate coupling scheme prevalent for N > 90 and the oblate coupling scheme present for N < 86. A detailed knowledge of the shape change in ^{154}Dy presents a stringent case for testing theoretical calculations.

In order to trace the behavior of the yrast band above the shape-transition region and extend our knowledge about the nuclear decay mode into the pre-yrast region, it is of importance to get information not only about

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the level energies and spins, but also about other properties of the levels, such as the lifetimes (and magnetic moments) which are more sensitive to the nuclear wavefunctions. This was the purpose of this experiment, which used the phase-I Compton-suppression germanium (CSG) array and the BGO multiplicity filter described elsewhere in this report. The data, obtained with the $^{122}Sn(^{36}S,4n)$ reaction at 165 MeV from a thick target in a two-day run and from a thin target in an eleven-hour run, enabled us to extend the yrast band to spin 44^+. Some ambiguities above 28^+ in the previous experiment were removed. A second positive-parity band and the negative-parity band were also extended to much higher spins. The very clean spectra from CSG detectors allowed observation of detailed lineshapes (see Fig. II-22). Hence the extraction of state and feeding times of the fast gamma rays ($\tau < 1$ ps), with the Doppler-shift attenuation method (DSAM), was possible.

The results indicate that the yrast line is collective at low spins, manifests backbending due to rotational alignment, and for $I \geqslant 32$ exhibits an onset of the oblate coupling scheme. A sequence of levels connected by stretched E2 transitions, which show large gains in energy with respect to a liquid-drop reference (Fig. II-23) is lowest in energy. At the highest spins the lifetime results suggest a return to collective structures. The feeding of yrast states exhibit both fast (collective) and slow (~ 10 ps) components, implying the coexistence of aligned-particle and collective configurations in the vicinity of the yrast line. Although the intensity of the transition depopulating the state I = 44 was still quite high (~ 10%), for I > 44, the decay pathway seems to suddenly fragment into many pieces, and the decay times indicate a predominance of collectivity. Whether there is a connection between these two phenomena is not clear.

The transitions from levels with $I \leqslant 36^+$ do not show Doppler-smeared line shapes in the thick-target spectra, which imply longer lifetimes or feeding times. Even at spin 44^+, there clearly exists feeding with long lifetimes. The slow lifetime and feeding time cannot generally be measured by DSAM, rather the recoil-distance method (RDM) is required and an experiment is planned. Since the yrast transitons with I > 44 are obviously much weaker (<2%) and also Doppler-broadened, an extension of the level scheme requires more statistics with a thin target, where the short-lived lines will all be fully Doppler-shifted but not significantly broadened. Thus data from a RDM

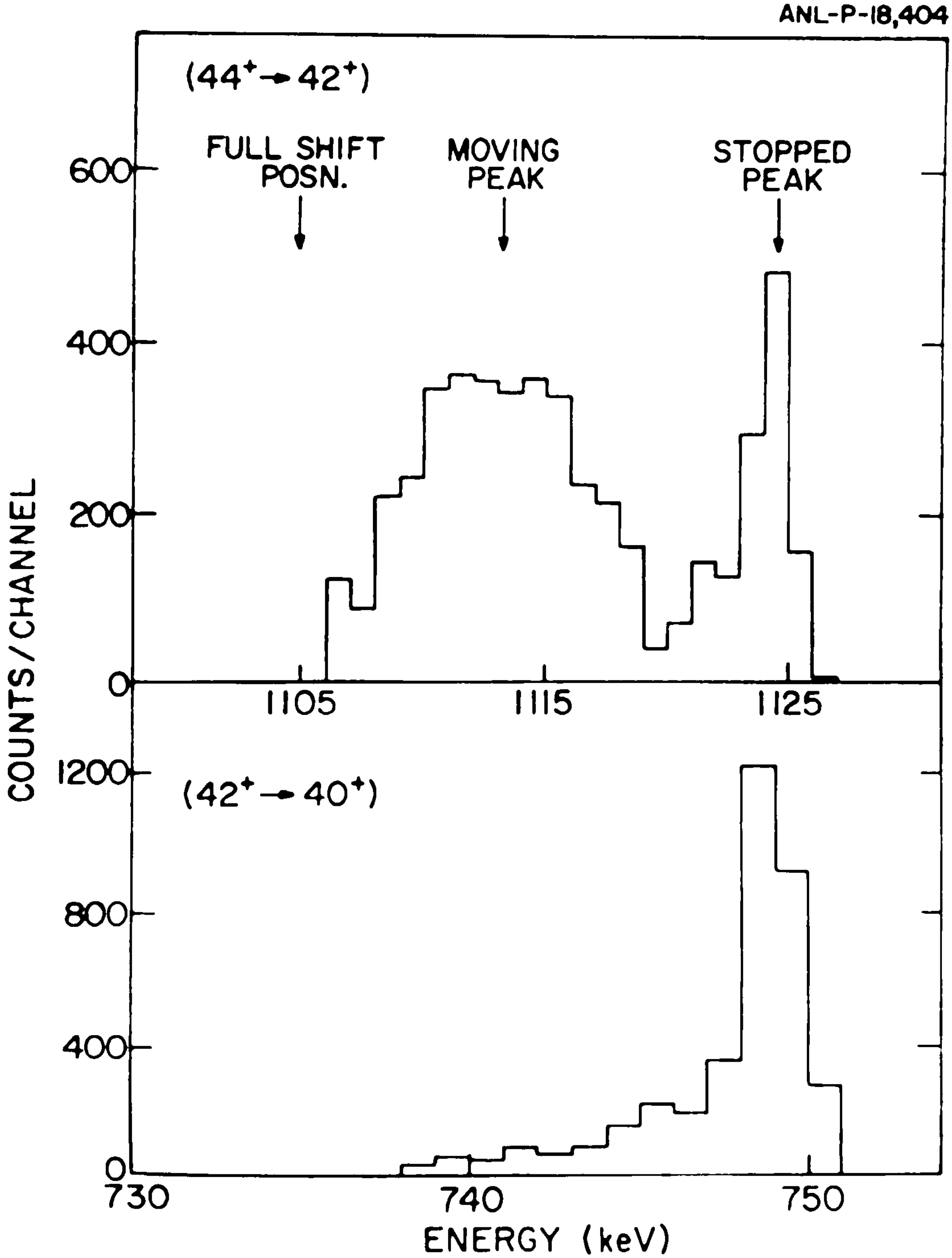

Fig. II-22. Lineshapes after background subtractions and smoothing.

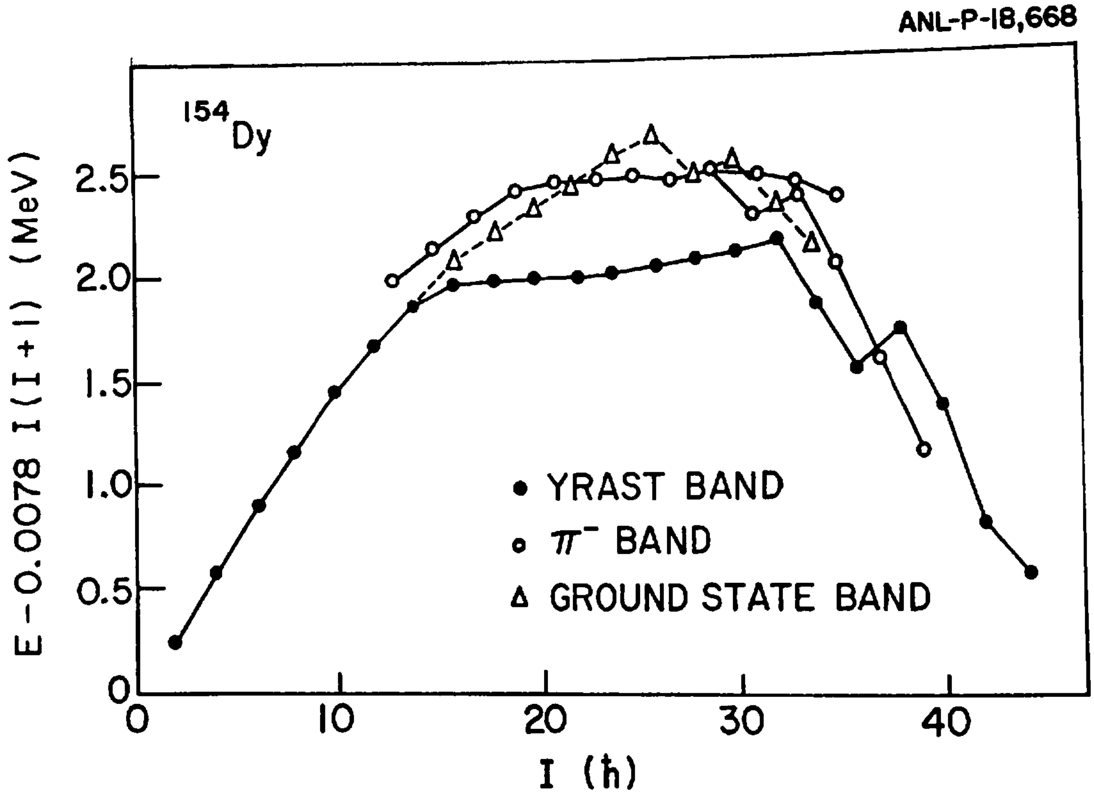

Fig. II-23. Level energies compared to a liquid-drop reference.

measurement will simultaneously yield information on the level structure above spin 44, as a thin target is used.

Meanwhile, the analysis effort is concentrating on the ^{153}Dy nucleus produced in the same experiment through the (^{36}S,5n) reaction. Preliminary results indicate that it will be possible to extend the oblate single-particle structure observed in earlier experiments towards higher spins.

f. Level Structure of ^{147,148}Gd up to I > 40 (M. Piiparinen,* M. W. Drigert,† R. V. F. Janssens, I. Ahmad, J. Borggreen,‡ R. M. Chasman, P. J. Daly,* H. Emling, U. Garg,† Z. W. Grabowski,* R. Holzmann, T. L. Khoo, W. C. Ma, M. Quader,* D. C. Radford,§ and W. Trzaska*)

The level structure of nuclei in the vicinity of the doubly-magic ^{146}Gd (Z=64, N=82) has been studied at this laboratory for quite some time. In the past, a large effort was placed on the investigation of the behavior up to the high spin of ^{147}Gd in a collaboration beteween Argonne, Purdue and the NBI, Copenhagen. The results of this work have been submitted for publication and can be summarized as follows:
(a) states up to an excitation energy of ≈ 17 MeV and a spin of 79/2 were established, (b) the resulting level scheme is characteristic of the single-particle nature of the yrast line up to the highest states with no evidence for collectivity, (c) the measured lifetimes of the states confirm the single-particle nature of the various states, (d) shell-model calculations using a deformed potential support the interpretation. With the new Argonne-Notre Dame BGO γ-ray facility an experiment was carried out with the hope that the enhanced detection sensitivity would allow exploration of the yrast structure to higher spins and excitation energy. This measurement would also yield information on the link between the collective structure and the single-particle states in the region where single-particle states constitute the yrast line. Finally, information would be gained on the properties of the quasi-continuum. The ^{116}Cd(^{36}S,4 or 5n) reactions were used with 170-MeV ^{36}S

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beams from the ATLAS accelerator to populate ^{148}Gd and ^{147}Gd with almost equal strength. On the basis of the 8 10^7 γ-γ coincidence events the ^{148}Gd level scheme, previously known up to spin 21, has been extended to spin 44. The scheme, consisting of about 100 levels accommodating 170 transitions, features irregularly-spaced yrast excitations of the aligned-particle type continuing all the way up to ~16.5 MeV (see Fig. II-24). When examining the structure of the highest states ($I > 35\ \hbar$) three new features appear: (i) the incremental energy per unit spin is much smaller than at lower spin, i.e the effective moment of inertia deduced for these states is very large, perhaps the largest seen in this mass region; (ii) above spin 36, all the transitions are of E2-character, in sharp contrast with the structure at lower spin where many dipole transitions compete favorably; (iii) at the highest spins fast transitions appear with enhancement factors of at least 40 with respect to the single-particle estimates. Clearly, a change of structure occurs above $I \simeq 35$ and calculations are under way to understand the nature of this change.

In ^{147}Gd, the level scheme was also extended further (see Fig. II-25). Between 8- and 14-MeV excitation energy many new near-yrast states have been identified. The level scheme has also been extended up to 18.5 MeV. All states observed are still of single-particle character. The analysis is continuing on both ^{148}Gd and ^{147}Gd. The emphasis is now placed on the properties of the quasicontinuum radiation. In particular, in the γ-γ coincidence matrix one hopes to search for correlated events which could be evidence for rotational structure indicative of large deformations.

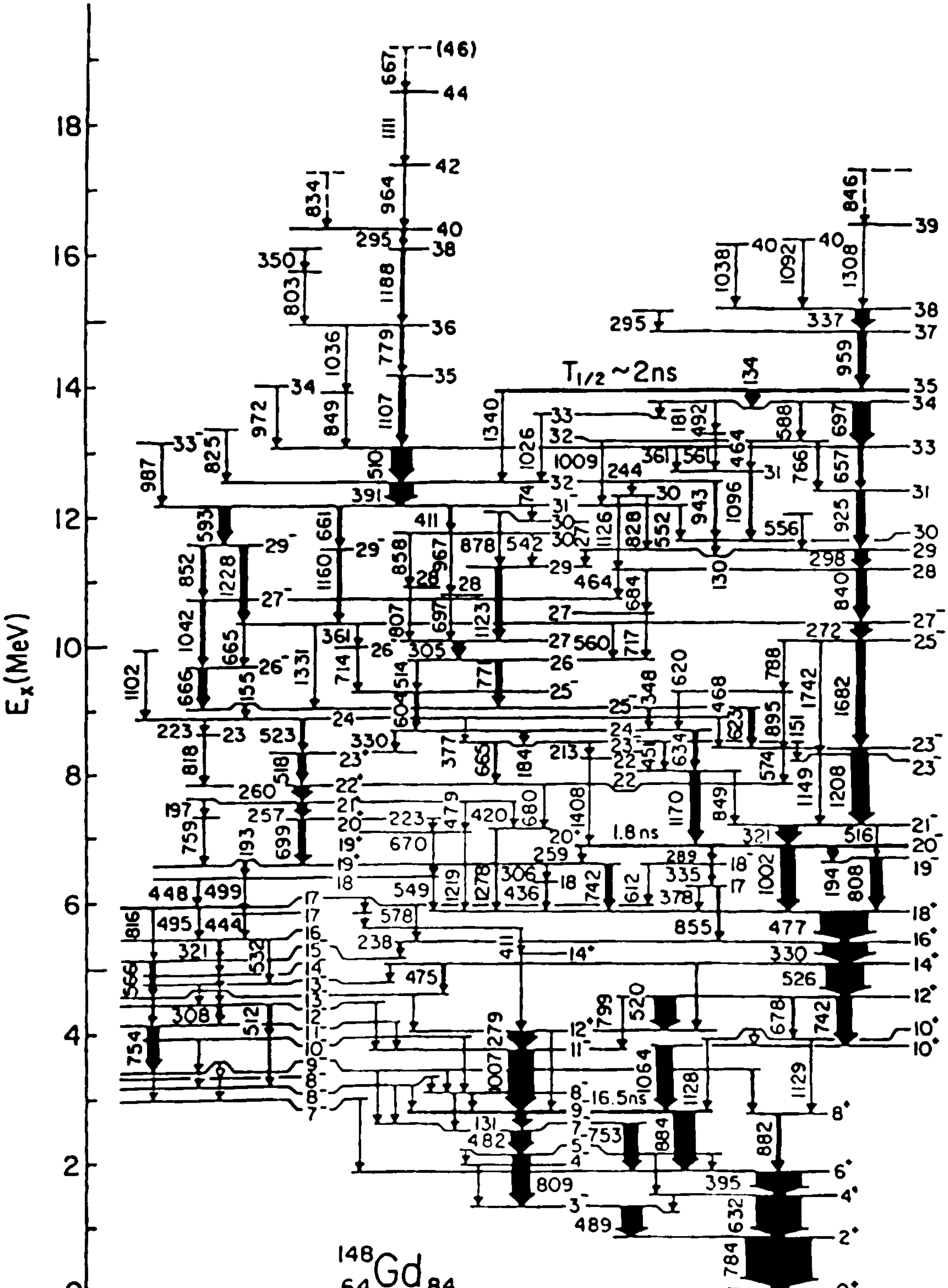

Fig. II-24. The ^{148}Gd level scheme. The widths of the transition arrows are proportional to the γ-ray intensities observed in the ^{116}Cd(^{36}S,4n)^{148}Gd reaction.

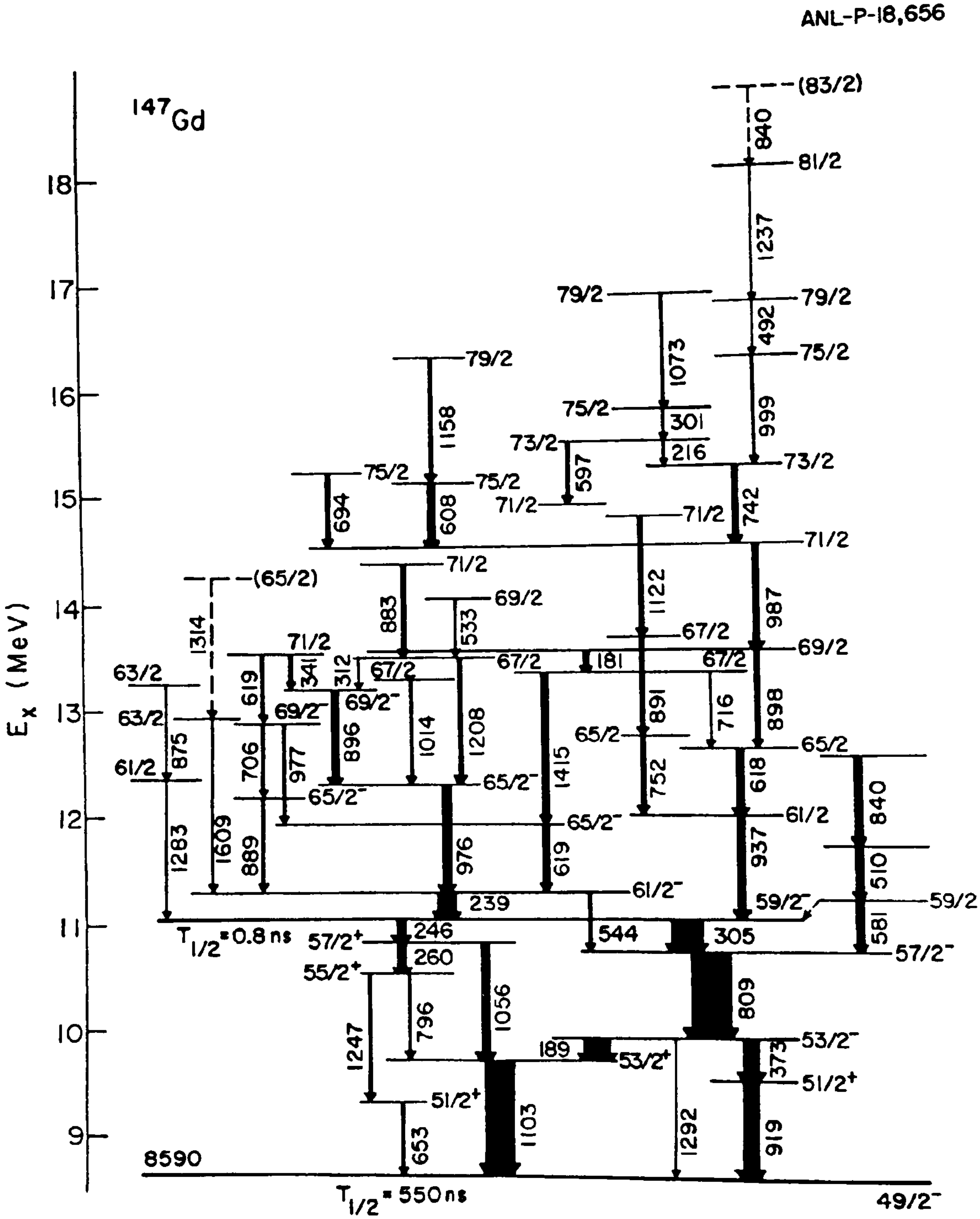

Fig. II-25. Level scheme of ^{147}Gd at high spin. Only transitions above the 550 ns isomer are shown.

g. **Lifetimes of Very High-spin States in ^{156}Dy Through DSAM**
(H. Emling, I. Ahmad, B. Dichter, R. Holzmann, R. V. F. Janssens, T. L. Khoo, M. Drigert,* U. Garg,* P. J. Daly,† Z. Grabowski,† M. Piiparinen,† M. Quader,† and W. Trzaska†)

Compton-suppressed Ge detectors yield γ spectra with not only high resolution but very low background, particularly when only a single channel is selected, e.g. by coincidence with specific γ rays. The quality is such that the line shapes of individual lines reflect not only the lifetime of the decaying state but also the feeding history. A first attempt to exploit these features to measure lifetimes and feeding times of high-spin states in ^{156}Dy has been performed with the BGO γ-ray facility, where 6×10^7 coincidences were recorded with the ^{124}Sn(^{36}S,4n) reaction. ^{156}Dy with N = 90 is the lightest Dy isotope where deformation becomes well established. Thus it is of interest to establish if the deformation is altered by rapid rotation, e.g. if triaxial and oblate shapes set in. In addition, we would like to study the evolution of the quasicontinuum states with spin internal excitation energy (above the yrast line) and neutron number by examining the total γ spectra of different Dy isotopes.

The preliminary results of this experiment can be summarized as follows: (i) lifetimes have been obtained for all yrast states in ^{156}Dy with spins between $I < 28^+$ and $I = 40^+$. (ii) for states with spin $I < 30\ \hbar$ good agreement is found with the results of an earlier GSI experiment using the recoil-distance method. (iii) the value of the B(E2)'s for states with spin $28^+ < I < 40^+$ remains essentially constant.

These results suggest that there is no significant change in deformation between $I \approx 28^+$ and $I \approx 40^+$ even though changes in the structure of the nucleus are inferred from the level energies.

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h. **Octupole Deformation in Neutron-rich Barium Isotopes** (W. R. Phillips, I. Ahmad, H. Emling, R. Holzmann, R. V. F. Janssens, T. L. Khoo, and M. W. Drigert*)

Recent mean-field calculations indicate the presence of octupole deformation in the ground states of neutron-rich barium isotopes. To test these predictions we have studied the structure of neutron-rich barium nuclei produced in the fission of ^{252}Cf. Detailed γ-ray spectroscopy measurements were performed with the Argonne-Notre Dame BGO γ-ray facility. The source consisted of 60-μCi ^{252}Cf deposited on a berylium cylinder with an 8-mg cm^{-2} Be window. Level schemes for ^{142,144,146}Ba (shown in Fig. II-26) were deduced from the detailed analysis of the γ-γ coincidence events. Transitions known from previous decay studies were used to identify γ rays and level energies in these nuclei. The present work provides the most extensive level schemes available in neutron-rich nuclei. In ^{144}Ba, levels up to spin 15 $\hbar$ were identified. We find interlaced positive- and negative-parity levels connected by fast electric-dipole transitions in ^{144}Ba and ^{146}Ba. Both these properties are signatures of reflection asymmetry and, in the past, have been used to deduce octupole deformation in the mass-224 region. Our results suggest that ^{144}Ba and ^{146}Ba are reflection symmetric in the ground state but attain octupole-deformed shapes at spins above 7 $\hbar$, which is in agreement with the recent calculations of Nazarewicz and Leander. The present studies provide the first evidence for reflection-asymmetric shapes in medium-mass nuclei. Analysis of the data to deduce the structure of other neutron-rich nuclei produced in the fission of ^{252}Cf is in progress.

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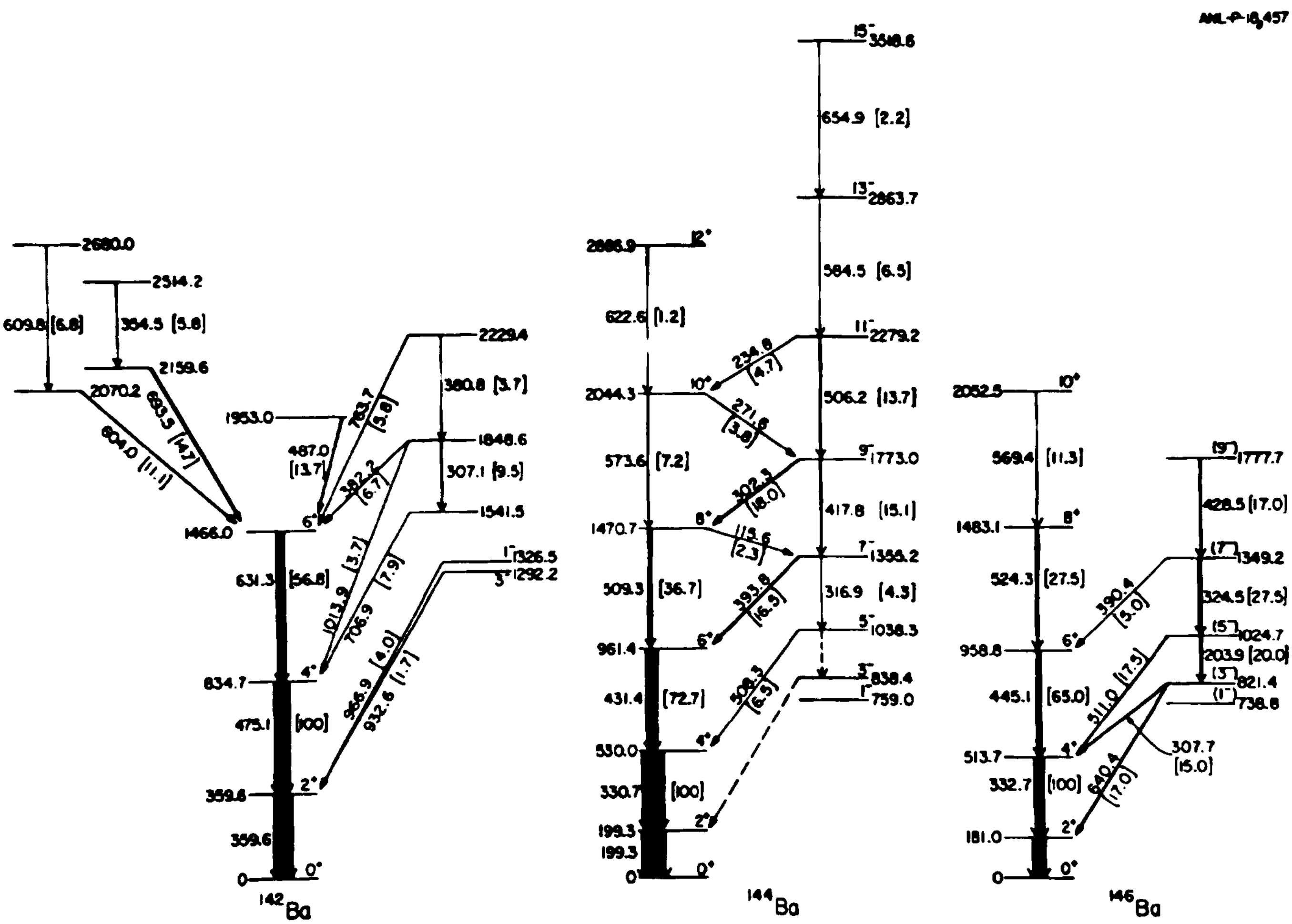

Fig. II-26. Partial decay schemes for $^{142-146}$Ba. The numbers in square brackets are the relative intensities of γ rays in coincidence with the $2_1^+ \to 0_1^+$ γ ray in each nucleus. The errors on the relative intensities vary from ~25% for the weak γ rays to ~5% for the most intense. The measured populations of ^{142}Ba, ^{144}Ba, and ^{146}Ba were in the ratios 0.68:1.00:0.29. The errors on the level energies and γ-ray energies are 0.2 keV or better; there is an additional uncertainty of 0.2 keV on the absolute energies.

i. **Angular Momentum in the Fission Process** (W. R. Phillips, Y. Abdelrahman,* J. Durell,* W. Gelletly,* I. Ahmad, R. Holzmann, R. V. F. Janssens, T. L. Khoo, W. C. Ma, and M. W. Drigert†)

The Manchester group has previously made extensive studies at Daresbury Laboratory of the angular momentum carried by fission fragments following heavy-ion fusion reactions by measuring prompt γ-ray multiplicities using NaI detectors. The $^{19}F + ^{197}Au$ system exhibited a marked variation in multiplicity with fragment mass. Within the framework of the statistical scission model this variation could be related to primary fragment shapes at scission. However, this variation in multiplicity could be simply due to nuclear structure effects in the secondary fragments, and hence not be related to the fission process.

In order to investigate this system in more detail, prompt γ rays produced in the bombardment of ^{197}Au by 120-MeV ^{19}F ions have been studied using the Argonne-Notre Dame γ-ray facility. Gamma-gamma coincidence spectra have been analyzed to establish partial decay schemes for fission fragments. So far decay schemes for 30 nuclei have been determined, for secondary fragments ranging from Se to Xe. These decay schemes have been analyzed to determine the average angular momentum at which observed levels are populated. From statistical evaporation model arguments it is expected that the average angular momentum of the primary fragments at scission can be obtained by adding the small change in angular momentum brought about by statistical γ-rays. The sum of the secondary fragment correlates well with the overall prompt multiplicities measured previously, implying that the number of unobserved statistical γ rays is essentially constant as a function of mass asymmetry. Further, the average spins at which the observed levels of the secondary fragments are populated are indeed varying with fragment mass (Fig. II-27). This confirms our earlier supposition that the primary fragments are being formed at scission with average angular momenta that vary with fragment mass. This seems most likely to be a reflection of a variation in the shape of the hot nuclei produced in fission.

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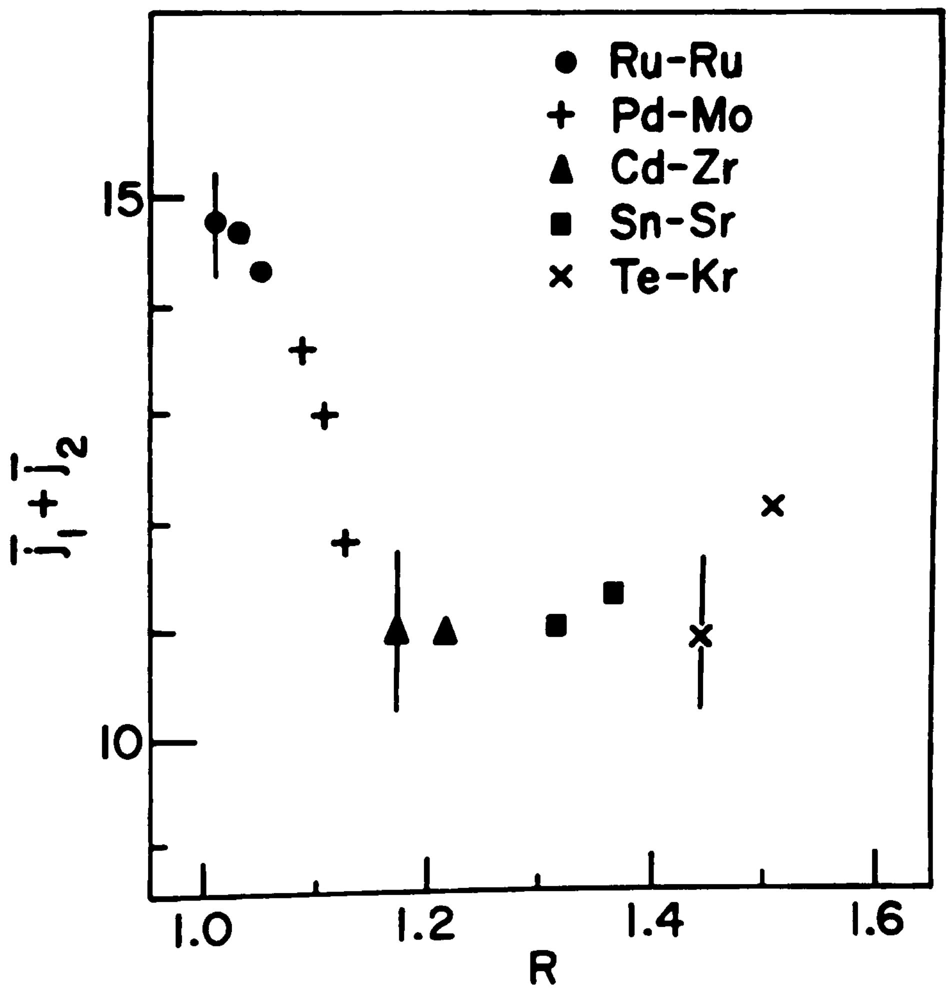

Fig. II-27. A plot of the sum of the average angular momenta at which observed levels in the secondary fragments are populated against the ratio of the masses of the associated fragments.

j. **Level Structure of ^{223}Ra and ^{225}Ra** (I. Ahmad, R. R. Chasman, R. Holzmann, R. V. F. Janssens, W. C. Ma, B. Dichter, T. L. Khoo, and M. W. Drigert*)

It has now been well established that ^{223}Ra and ^{225}Ra possess octupole deformation. In both nuclei only two parity doublets 1/2± and 3/2± have been identified. According to the octupole deformation model there should be a $K\pi = 5/2^-$ band in ^{225}Ra, which is the negative-parity partner of the $5/2^+$ band at 236 keV. In addition, a $K^\pi = 7/2\pm$ doublet is predicted by Leander at low excitation energy (below 300 keV) in ^{225}Ra. In our earlier studies we have not identified any of these bands. We have now used the high sensitivity of the Compton-suppressed Ge detectors of the Argonne-Notre Dame BGO γ-ray facility to investigate these bands. A mass-separated ^{229}Th source was used for alpha-gamma coincidence measurements. We used a passivated ion-implanted silicon detector for the detection of α-particles. These detectors have resolutions (FWHM) of <10 keV and have very small tailing. Preliminary results of the data analysis indicate that the $5/2^-$ band is at 392 keV. However, we do not observe any K = 7/2 band. We plan to perform alpha-electron coincidence measurements to confirm the assignment of the 392-keV level. The large spacing between the $5/2^-$ and $5/2^+$ states indicates an octupole vibrational picture for these bands instead of octupole deformation shape deduced from the $1/2^\pm$ doublets.

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k. **Evolution of Nuclear Structure with Increasing Spin and Internal Excitation Energy in ^{152}Dy** (R. Holzmann, I. Ahmad, B. K. Dichter, H. Emling,* R. V. F. Janssens, T. L. Khoo, W. C. Ma, M. W. Drigert,† U. Garg,† D. C. Radford,‡ P. J. Daly,§ Z. Grabowski,§ H. Helppi,§ M. Quader,§ and W. Trzaska§)

Our study of the total γ radiation from ^{153}Ho published last year demonstrated the power of the Compton-suppressed Ge detectors (CSG) in unravelling details of the quasicontinuum spectra. The total γ-ray spectrum emitted by ^{152}Dy has been measured in the two reactions ^{76}Ge(^{80}Se,4n) and ^{120}Sn(^{36}S,4n). In the experiment with the ^{80}Se beam, 4 CSG's located at

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0°,45°, 90° and 147° with respect to the beam axis were used. In the second measurement with the ^{36}S beam, 8 CSG's placed at 34°, 90° and 146° were used. In both cases a 14-element multiplicity filter provided the necessary channel selection by tagging on the decay of the 60-ns isomer in ^{152}Dy. The measured spectra were decomposed into their constituent parts, trees, grass, soil and statisticals [Fig. II-28(a)] and from the extracted multiplicities, multipolarities, spectral shapes and decay times, the average decay path has been reconstructed. The yrast single-particle structures have been shown to give way to highly collective bands at internal excitation energies >1.5 MeV. These collective bands manifest themselves through the presence of a bump of stretched E2 transitions in the spectra [Fig. II-28(b)]. This bump has a much larger multiplicity in the spectra obtained with the Se reaction (where the average entry spin is 55$\hbar$) than in those measured with the S beam (average entry spin 47$\hbar$), thereby confirming that continuum states at the highest spins are decidedly collective. The lifetimes associated with he E2 bump and the underlying statistical component of the spectrum were determined by fitting the data [Fig. II-28(c)] with a simple model that takes into account the competition between in-band collective E2 transitions and out-of-band statistical E1 decay at high excitation energy and spin. Its basic ingredients are: (i) statistical E1 decay governed by the level densities and the giant-resonance strength function based on the classical energy-weighted sum rule; and (ii) collective bands characterized by a transition quadrupole moment Q_t, an effective momement of intertia I_{eff} and a cut-off energy U_o. γ cascades were generated in a Monte Carlo procedure starting from an entry region centered around the measured average entry points. The experimentally-observed E2 and statistical multiplicities, spectral shapes and the measured Doppler shifts were simultaneously reproduced. Fitting the model to the data [Fig. II-28(d)] yielded a value for $Q_t = 7.0^{+2.5}_{-1.5}$ eb, which implies a deformation $\beta = 0.32$ similar to those observed in neighboring deformed nuclei. Thus, the bulk of the collective bands are not associated with superdeformed shapes.

These results have been submitted for publication. The picture summarized above could be generalized to deformed nuclei by removing the collectivity cut-off U_o. Measurements of the properties of continuum radiation in deformed rare-earth nuclei are being analzyed.

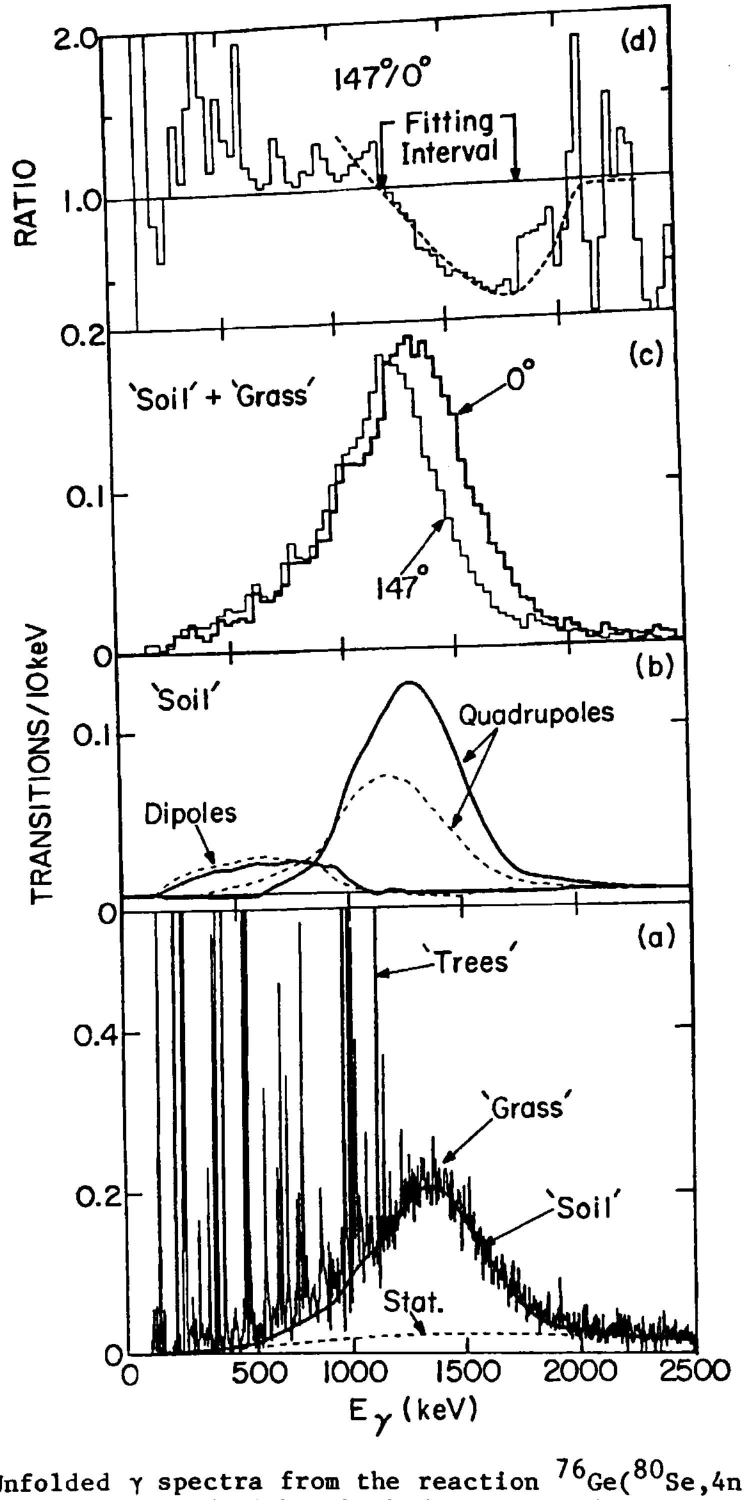

Fig. II-28. Unfolded γ spectra from the reaction $^{76}Ge(^{80}Se,4n)^{152}Dy$ at 311 MeV measured with a backed target. (a) Total spectrum measured at 0°. (b) Dipole and quadrupole soil components (full line) corrected for angular distributions and Doppler shifts; corresponding spectra from the $^{120}Sn(^{36}S,4n)$ reaction are shown as dashed lines. (c) Sum of soil and grass parts observed at 0° and 147°. (d) Ratio of the spectra in (c) (147°/0°) compared with model calculations discussed in the text (dashed line).

i. Sign of M1/E2 Mixing Ratios in Transitions Between Levels of the 8^- Band in ^{178}Hf (R. V. F. Janssens, I. Ahmad, M. W. Drigert,* R. Holzmann, T. L. Khoo and G. T. Emery†)

In ^{178}Hf there are two excited rotational bands with the quantum numbers $K^\pi = 8^-$. Two such bands are expected for this Z=72, N=106 nucleus, one based on the two-quasineutron configuration [624↑] + [514↓], and the other on the two-quasiproton configuration [514↑] + [404↓]. From the relative excitation probabilities of the two 8^- levels in beta decay and electron capture, it is known that the lowest 8^- state is approximately 2/3 neutron and 1/3 proton, the other state being the orthogonal partner. The mixing between the neutron and proton configurations can be attributed to the neutron-proton residual interaction and, in the adiabatic limit of the rotational description, would be expected to be the same for all levels in the bands. The M1/E2 mixing ratios for the in-band transitions changing I by one unit would then be expected to be the same for all transitions, within about 5%.

From measurements of conversion coefficients α_K performed some years ago[1] it was established that the M1/E2 mixing ratios in the lowest $K=8^-$ band (fed in the decay of the 16^+ isomeric state) are not independent of I. Thus the residual neutron-proton interaction appears to be spin dependent. In this measurement α_K is only sensitive to the square of the mixing ratio and, thus, the sign is unknown. The latter is of interest for the interaction. This sign can be obtained in a γ-γ correlation experiment. A 20-nCi ^{178}Hf source ($t_{1/2}$ = 31 y) was placed inside the Argonne-Notre Dame γ-ray facility. Eight Compton-suppressed Ge detectors were used. In a period of 20 days a total of 10^6 coincidence events were recorded. The analysis of the experiment is in progress. It is hoped that the statistical accuray is sufficient to accurately determine the sign of the mixing ratio.

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[1] J. Van Klinken et al., Nucl. Phys. A339, 189 (1980).

m. **Shell-model States Around N = 82** (P. J. Daly,* Z. W. Grabowski,* J. McNeill,* H. Helppi,* M. Piiparinen,* M. Quader,* Z. Trzaska,* R. Holzmann, R. V. F. Janssens, and T. L. Khoo)

The systematic study of very proton-rich nuclei around N = 82 has continued in order to test further the applicability of the shell model in this region. Shell-model calculations, using ^{146}Gd as a closed core have been extremely successful previously in describing the level structure of N = 82 and N = 83 nuclei.

We have completed our study of the level structure of the proton-rich N = 83 nuclei ^{150}Ho and ^{152}Tm. Isomers have been identifed in ^{150}Ho at 1.096, 2.625 and ~8.0 MeV (with respective half lives of 18±2, 84±8 and 751±36 ns) and in ^{152}Tm at 2.555 and ~6.3 MeV (with respective half lives of 294±12 and 42±5 ns). The detailed level schemes of both nuclei have been established up to 2.6 MeV above their $(\pi h_{11/2}\nu f_{7/2})9^+$ ground states. In both nuclei, states with the configuration $(\pi h_{11/2})\nu f_{7/2}$ form the main yrast sequences up to the 17^+ isomers in the vicinity of 2.6 MeV. The level energies agree very well with shell-model predictions, and the variation in the observed $B(E2,17^+\rightarrow15^+)$ values can be explained convincingly. Other levels located in both nuclei are described as $9^+ \times 3^-$ octupole, $(\pi h_{11/2})^n\nu i_{13/2}(v=2)$, $(\pi h_{11/2})^{n-1}\pi s_{1/2}\nu f_{7/2}$ (v=4) and $(\pi h_{11/2})^{n-1}\pi d_{3/2}\nu f_{7/2}(v=4)$ states, which extend the systematics of such excitations in the N=82 and N=83 isotones. These results have been summarized in a recent publication.[1]

Work is continuing on the structure of ^{151}Er, an even-odd nucleus with four valence protons outside the ^{146}Gd core and a single valence neutron. This nucleus was investigated by performing a comprehensive $\gamma\gamma$ coincidence experiment with the $^{93}Nb(^{60}Ni,pn)$ reaction at 240 MeV. We employed the familiar recoil-catching technique where the recoiling nuclei are collected downstream from the target on a foil surrounded by the Ge detectors, thereby enlarging the detection sensitivity for delayed γ rays by shielding the detectors carefully from prompt radiation from the target. The resulting level scheme is shown in Fig. II-29. Three isomers were identified with the following excitation energies an half lives: 1141 keV ($t_{1/2}$ = 9.5 ± 1.7 ns),

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†Lappeenranta University of Technology, Finland.
[1]J. McNeill et al., Z. Physik A325, 27 (1986).

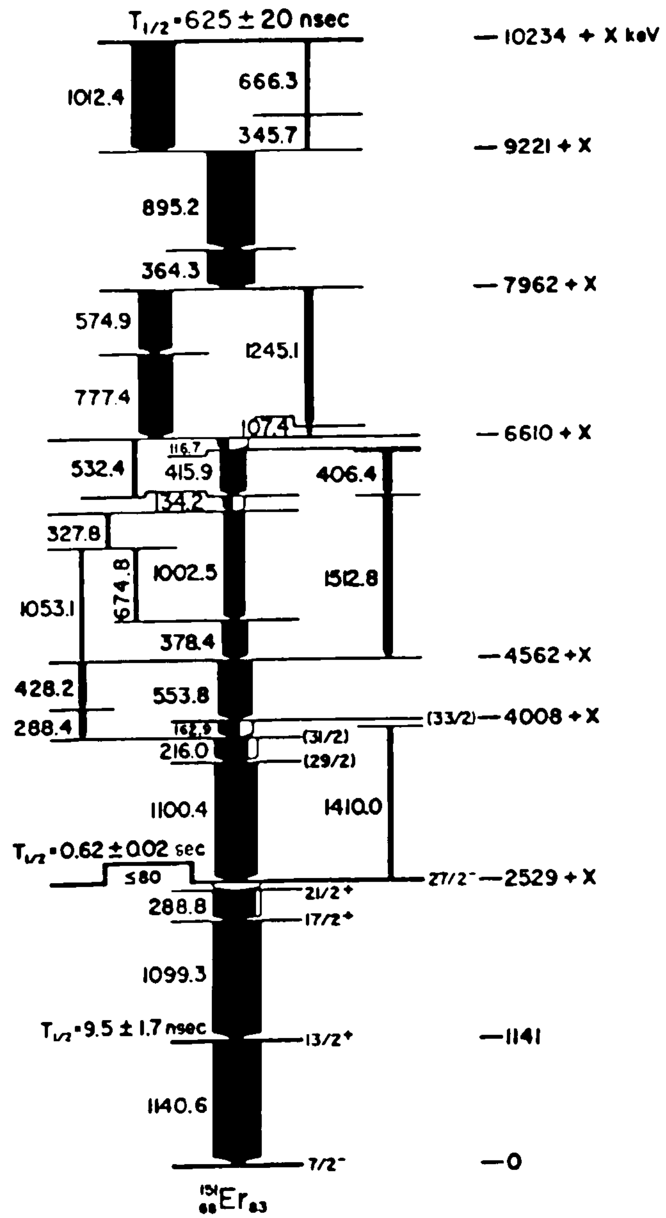

Fig. II-29. The ^{151}Er level scheme up to he 625 nsec isomer. Widths of transition arrows, for γ rays above the $27/2^{-}$ state, are proportional to he off-beam intensities. Arrow widths for transitions below the $27/2^{-}$ isomer are equal to he sum of the 1100- and 1410-keV transition arrow widths. The value of X is < 80 keV.

~2529 keV ($t_{1/2}$ = 0.62 ± 0.02 s) and ~10.2 MeV ($t_{1/2}$ = 625 ± 20 ns). A detailed level scheme has been derived. The decay of the 0.62 s isomer appears to be very similar to he well-established $27/2^- \rightarrow 21/2^+ \rightarrow 17/2^+ \rightarrow 13/2^+ \rightarrow 7/2^-$ decay of the 0.50 s $(\pi h_{11/2}{}^2 \nu f_{7/2})27/2^-$ isomer in the isotone ^{149}Dy nucleus. The level structure above this $27/2^-$ isomer is more difficult to interpret in view of the complexity of the observed level structure and the present lack of information on the multipolarity of many of the transitions. Nevertheless, some similarities with ^{149}Dy are again striking. In particular, $27/2^- \times 3^-$, $\pi h_{11/2}{}^3 d_{5/2}{}^{-1} \nu f_{7/2}$ and $\pi h_{11/2}{}^3 g_{7/2}{}^{-1} \nu f_{7/2}$ excitations are suggested. However, without firm spin-parity assignments, further speculation about structural interpretation seems futile at this point.

Work is also continuing on the ^{149}Er and ^{151}Yb nuclei produced respectively with the ^{92}Mo(^{60}Ni,2pn) at 255 MeV and ^{96}Ru(^{58}Ni, 2pn) at 250 MeV. Three isomers are present in ^{149}Er (Fig. II-30) with the following excitation energies and half lives: 742 keV($t_{/12}$ ~10.8 s), 2.6 MeV ($t_{1/2}$ ~0.6 μs) and 3.25 MeV ($t_{1/2}$ ~ 4.8 μs). Most of the observed level structure can be interpreted within the shell model as arising from $(\pi h_{11/2}{}^n \nu h_{11/2}{}^{-1})$, $(\pi h_{11/2}{}^n n s_{1/2}{}^{-1})$ and $(\pi h_{11/2} \nu d_{3/2}{}^{-1})$ excitations. Similarities with the ^{147}Dy isotone have been recognized. In the case of ^{151}Yb, the experimental situation is more difficult. The cross section for the reaction channel of interest is very small. Nevertheless, we have tentative evidence for a 26-μs isomer accompanied by several transitions representing the main decay path. The analysis is still in progress.

In most cases studied so far, spin and parities have been assigned to the measured states by relying heavily on shell-model considerations. Clearly, experimental confirmation is needed. This is expected to come mainly from measurements of conversion electrons which are planned with the superconducting electron spectrometer currently under construction at Purdue.

Furthermore, advantage will be taken of the Argonne-Notre Dame BGO γ-ray facility to study ^{150,149}Er and ^{149}Ho in great detail. The excellent sensitivity provided by the instrument makes it feasible to extend the level schemes obtained in our earlier studies to much higher spins. We note that ^{150}Er is the counterpart in the rare-earth region of ^{212}Rn, a nucleus with 4 valence protons outside a ^{208}Pb core. The well-studied yrast level scheme of ^{212}Rn is often the showpiece chosen a) to illustrate the generation of high

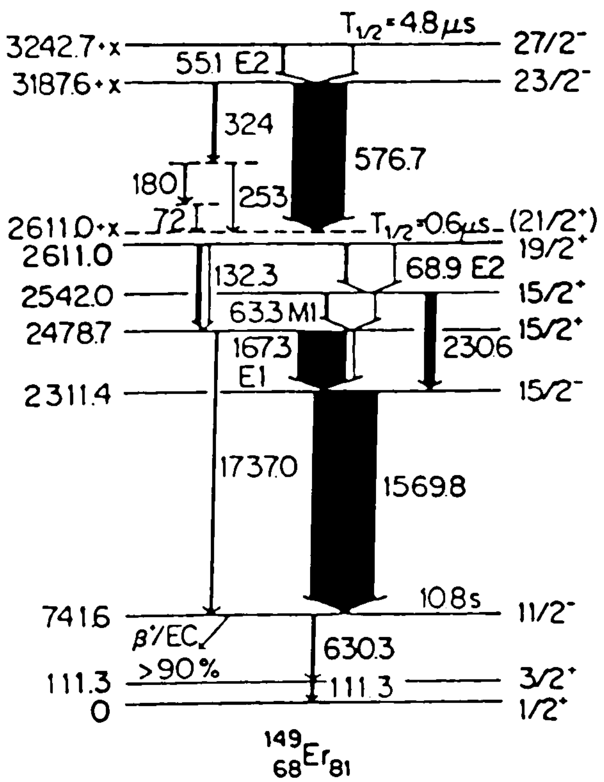

Fig. II-30. The level scheme of ^{149}Er. Widths of transition arrows are proportional to the intensities; where appropriate, internal conversion contributions are represented by unshaded areas. Multipolarities determined from intensity balance ae indicated.

angular momentum in nuclei in successive alignment of the orbital motions of individual nucleons and b) to test the predictive power of various calculations. Considering target availability and fission competition, ^{150}Er would appear to be a much more favorable case than ^{212}Rn for studying high-spin states in heavy-ion-induced reactions.

n. **Electromagnetic Transitions in Neutron-Rich Nuclei in the A ≃ 40 Region via Reactions of ^{36}S with ^{9}Be** (R. L. Kozub,* J. F. Shriner,* M. M. Hindi,* R. Holzmann, R. V. F. Janssens, T. L. Khoo, W. C. Ma, M. W. Drigert,† U. Garg,† and J. J. Kolata†)

The BGO γ-ray facility at ATLAS was used in conjunction with charged-particle detectors to test the feasibility of observing, in triple coincidence, the emission of two charged particles and a γ-ray from neutron-rich systems.

A small, cylindrical chamber (8.4-cm diameter × 7.5-cm high) which fits in the small cavity formed by the CSG's and BGO elements was designed and constructed to contain the target, magnets for electron suppression, a collimator, and two E-ΔE Si(SB) detector telescopes.

The target consisted of a 2.34-mg/cm^2-thick Be foil with 10 mg/cm^2 of Pb evaporated onto the downstream side to stop most of the heavy reaction products. An additional Pb foil of 7.5-mg/cm^2 thickness served to stop the ^{36}S beam, which had an energy of 100 MeV upon entering the target. The E-ΔE telescopes were placed in the forward direction at ±13° to detect light particles ($Z < 3$) which had enough energy to penetrate the beam stopper foil and the 40-μm-thick ΔE detectors. Each telescope subtended a solid angle of 0.14 sr. Three of the CSG's were positioned at ±90° with respect to the beam axis while the other four were positioned at ±150°. Data were collected for approximately 20 h at an average beam current of ~ 0.7 pnA. Energy and timing information from all CSG's and the telescopes and the multiplicity of BGO signals were recorded for all two-fold or higher-order coincidences among the CSG's and telescopes.

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Sorting of the data was performed at Tennessee Technological University. Spectra of γ rays emitted in coincidence with protons, deuterons, tritons, and α-particles have been obtained. From these spectra, it is clear that the most prominent reaction channels in which a charged particle is evaportated are p,n (leading to ^{43}K), p,2n (leading to ^{42}K), and α,n (leading to ^{40}Ar). We thus expect new structure information on the neutron-rich potassium isotopes to be revealed when the data are sorted in the γ-γ coincidence mode.

Spectra of γ rays emitted in coincidence with two charged particles ($\alpha\alpha,\gamma$) and ($\alpha p,\gamma$) have also been obtained. Two transitions which may be attributed to ^{37}S are observed, as well as four lines which can be attributed to ^{40}Cl with a high degree of confidence. A preliminary decay scheme for ^{40}Cl has been derived (Fig. II-31). Our proposed levels agree quite well with those deduced from earlier charge-exchange work, and the number of spacing of low-lying states would seem reasonable, based on the weak-coupling picture.

Late in December 1986 a much longer run on this experiment was performed in order to get a more complete picture of the structure of ^{40}Cl and to have some possibility of observing ^{43}Ar transitions via the 2p evaporation channel. Of course, new decay schemes and lifetime information on other neutron-rich nuclei, such as the above-mentioned potassium and sulphur isotopes, has also been acquired during this run.

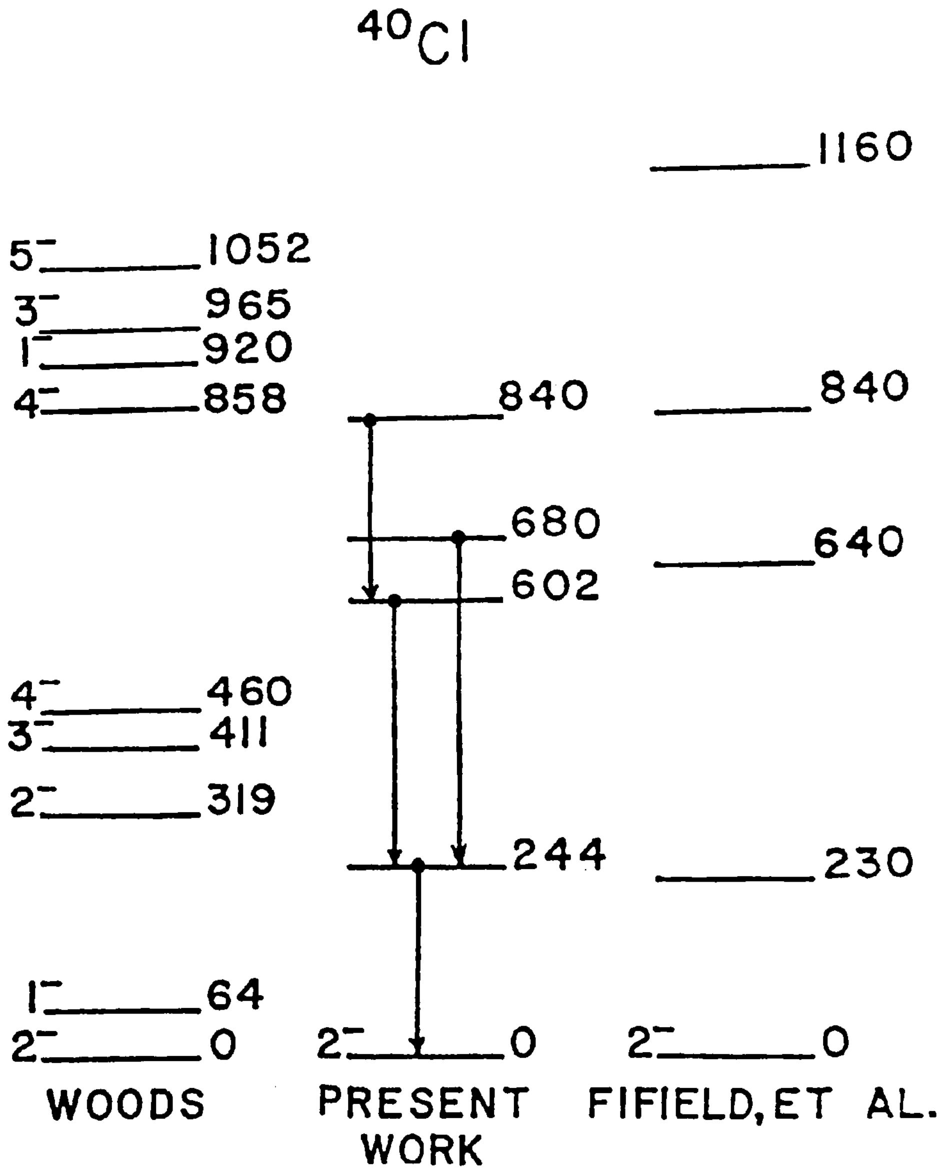

Fig. II-31. Tentative decay scheme and level diagram for ^{40}Cl. Also shown are levels observed by Fifield et al. and the prediction of Woods using the Chung-Wildenthal interaction.

o. **Recoil-distance Lifetime Measurements in ^{184}Pt** (U. Garg,* A. Chaudhury,* M. W. Drigert,* E. G. Funk,* J. W. Mihelich,* D. C. Radford,† R. Holzmann, R. V. F. Janssens, T. L. Khoo, and H. Helppi‡)

The collective structure of the highly neutron-deficient Pt (Z = 78) nuclei has been rather difficult to elucidate within the framework of the Interacting Boson Model (IBM) which has been eminently successful in the description of the higher-mass Pt isotopes. The lighter Pt nuclei show fairly large deformations not expected in the model. It has been asserted recently that if intruder proton orbitals (such as $h_{9/2}$) are accessible to build extra π-bosons, this effect is sufficient to explain the large deformation in the light Pt isotopes. An important feature of the aforementioned assertion is that proton pairs in the intruder orbitals would play a major role in the ground state of the highly-neutron-deficient Pt nuclei. The crossing between these $\pi(6h\text{-}2p)0^+$ states and the normal $\pi(4h)0^+$ states is expected to occur at ^{186}Pt/^{188}Pt, so that for A < 186 the ground states are primarily $\pi(6h\text{-}2p)$ states formed by these intruder protons.

Low-lying 0^+ excited states have been experimentally observed in these even-Pt nuclei at E ~ 500 keV. It is suggested that a mixing between the "normal" and "intruder" 0^+ states would account for an intriguing phenomenon observed: the moment of inertia for the ground-state bands in the highly-neutron-deficient even-mass Pt nuclei are significantly smaller than those for the associated "decoupled" bands in the neighboring odd-mass Pt nuclei. However, the arguments for this mixing and, thus, for the evidence of the "intruder" nature of the ground state, have so far been based only on the observed transition energies. A measurement of the B(E2)'s for the ground-state bands in the even Pt isotopes up to the high-spin states would provide a direct and clear evidence for the presence of this mixing and also reveal its extent; one expects to observe a gradual increase in the B(E2) values with the spin of the depopulating state until the full collective strength of the "unmixed" ground-state band is observed at the higher spins.

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The analysis of the lifetimes of the levels in the yrast band of ^{184}Pt was completed in 1986. The data were obtained in a recoil-distance measurement where the ANL plunger apparatus was used in conjunction with the sum spectrometer for the ^{154}Sm(^{34}S,4n) reaction at 160 MeV. B(E2) values were obtained for all yrast levels up to 18^+. A significant increase (by a factor of > 2.5) is seen between spins 2^+ and 10^+. This is in line with the picture of mixing outlined above. Beyond 10^+, a decline of the B(E2) values is also observed. The latter effect is similar to that observed in rare-earth nuclei after the onset of the "backbending" phenomenon and may be an indication for a change in the structure of the states along the yrast line (possibly a crossing of the g.s. band with a rotational band with an aligned $i_{13/2}$ neutron pair). These results have been published. Extensions of the measurements to the neighboring ^{186,182}Pt isotopes will be performed with the new BGO γ-ray facility. To this effect, the existing plunger apparatus has been modified so that it can be placed inside the setup. Measurements on the nuclei ^{189,191}Tl are also planned with the same equipment. The purpose of this experiment is to determine the quadrupole moment of the strongly-coupled bands seen in these single-proton-hole nuclei adjacent to the Z=82 closed shell.

D. ACCELERATOR MASS SPECTROMETRY (AMS)

Experiments with AMS focussed in the past year on a variety of different problems, each of them being unique in its technical and/or applied aspect. Utilizing ATLAS beams and the gas-filled Enge split-pole magnetic spectrograph for isobar separation, ^{60}Fe was detected in an iron meteorite at a level of ^{60}Fe/Fe = 3×10^{-14}. With the same technique the first measurement of the natural concentration of ^{41}Ca($t_{1/2}$ = 10^5 yr) in contemporary bone was performed. The result ^{41}Ca/Ca = $(2.0 \pm 0.5) \times 10^{-14}$ raises great hopes to extend direct dating of bone far beyond what is currently possible with ^{14}C($t_{1/2}$ = 5730 yr). A preliminary experiment to measure anomalous isotope ratios of stable silver isotopes in meteorites was performed at the Munich MP tandem. Such a measurement can trace the primordial existence of long-lived radioisotopes, which are now extinct, through the isotopic excess produced by in situ decay in early condensates of the solar system. The isotope ratio of the fission products ^{129}I/^{131}I was measured in fallout from the Chernobyl reactor accident using the AMS facility at the Weizmann Institute in Rehovot. From the measured ratio a reactor operating time of about two years could be estimated. Finally, an experiment to determine the half-life of the long-lived fission product ^{126}Sn($t_{1/2}$ = 10^5 yr) has been started at ATLAS.

a. **Isobar Separation in AMS with a Gas-Filled Enge Split-Pole Magnetic Spectrograph** (W. Henning, B. G. Glagola, J. G. Keller, W. Kutschera, Z. Liu,* M. Paul,† K. E. Rehm, and R. H. Siemssen‡)

In a typical AMS experiment, the radioisotope ions of interest are often masked by a much larger intensity of stable-isobar ions, even after being subjected to acceleration and magnetic and electric deflections. Since the minute mass differences of isobars cannot be resolved, the final isobar separation can only be achieved by using effects caused by their difference in nuclear charge. We have recently revived a technique first proposed by Fulmer and Cohen,[1] which is based on the fact that charge-changing processes of ions in gas, if they occur frequently enough in a magnetic-field region, lead to trajectories determined by the average charge state of the ion. For isobars of different nuclear charge, the mean charge state and consequently the average trajectories of the isobaric ion will be different.

We have recently used this method for isobar separation in two AMS experiments with ^{60}Fe (with ^{60}Ni as the stable isobar) and ^{41}Ca (^{41}K) at ATLAS. In these experiments the iosbaric ions were separated at 340 MeV (^{60}Fe-^{60}Ni) and 200 MeV (^{41}Ca-^{41}K) in an Enge split-pole spectrograph filled with a few Torr of N_2 gas. The pressure of the gas was adjusted so as to minimize the scatter in ion trajectories, which is dominated at low pressure by the statistics of the charge-changing processes and at higher gas densities by small-angle scattering and energy-loss straggling (Fig. II-32).

The measured isobar separations were well reproduced with a Monte-Carlo calculation.[2] One interesting aspect is the fact that the calculated relative difference in the mean charge states between two isobars ($\Delta\bar{q}/\bar{q}$) varies surprisingly slowly over a large range of incident energies, extending to quite low energies. For example one obtains values of 4.5% at 200 MeV and 3.4% at 20 MeV for the isobar pair ^{41}Ca-^{41}K. This result indicates the possibility of isobar separation at much lower incident energy than previously expected, which could be of great practical value for AMS measurements. Experiments are planned to verify these findings.

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†The Hebrew University of Jerusalem, Jerusalem, Israel.
‡Rijksuniversitaet, Groningen, The Netherlands.
[1] C. B. Fulmer and B. L. Cohen, Phys. Rev. 109, 94 (1958).
[2] W. Henning et al., Proc. Workshop on Techniques in Acc. Mass Spectrometry, eds. R.E.M. Hedges and E.T. Hall, Oxford 1986, p. 196.

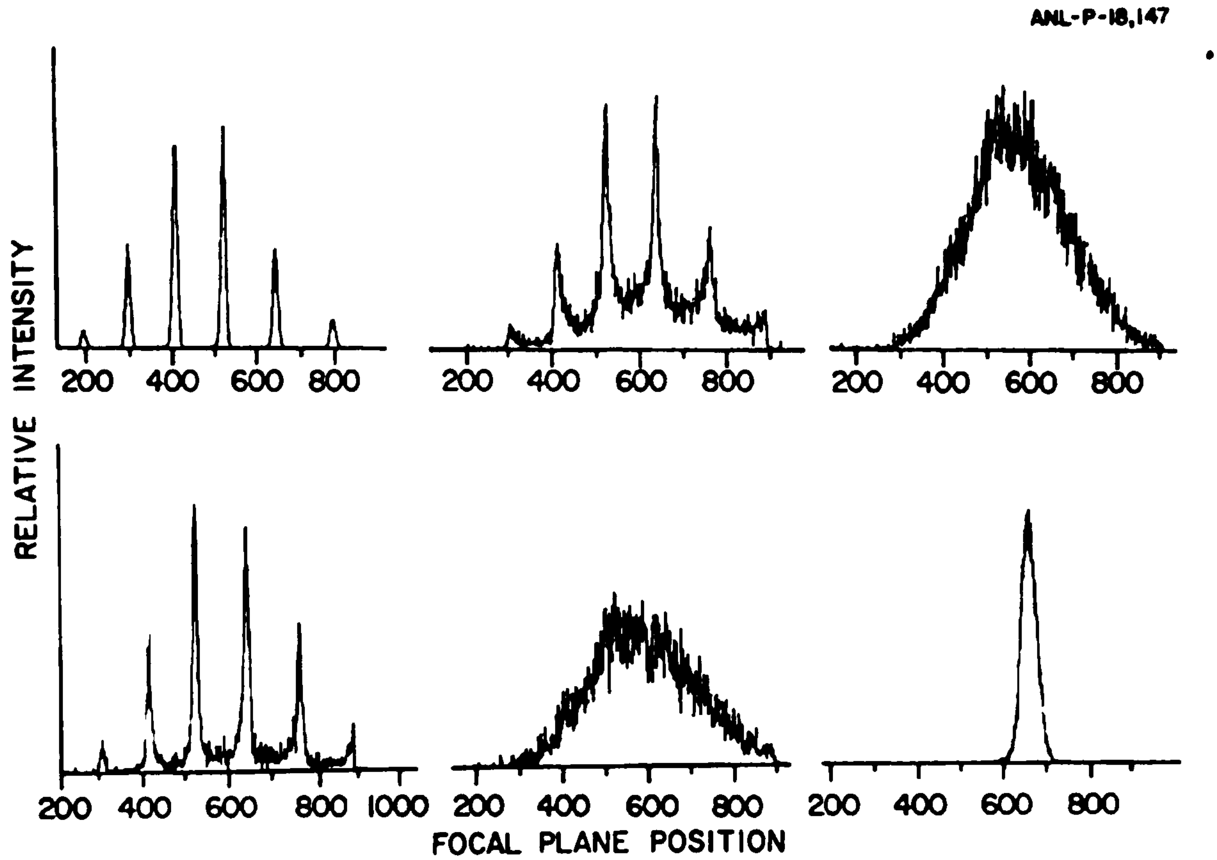

Fig. II-32. Charge-state spectra of ^{58}Ni ions with 300-MeV incident energy, measured in the focal plane of the Enge split-pole magnetic spectrograph; (a) thin gold target, vacuum (5×10^{-6} torr) in the spectrograph; (b)-(f) spectrograph filled with nitrogen gas at pressures of 2×10^{-3}, 2×10^{-2}, 0.5, 2.0 and 12 torr, respectively.

b. **^{60}Fe in Meteorites** (W. Kutschera, P. Billquist, B. G. Glagola, W. Henning, Z. Liu,* R. Pardo, M. Paul,† K. E. Rehm, R. K. Smither, and J. L. Yntema)

The interaction of cosmic rays with meteorites produces a number of long-lived radioisotopes which can be used to obtain information on both the target and the projectiles. Typical problems addressed are the irradiation history of meteorites and questions on their extraterrestrial and terrestrial ages. Another subject of interest is the constancy of the cosmic-ray flux over the long period of times meteorites are exposed.

A number of long-lived radioisotopes such as ^{10}Be($t_{1/2}$ = 1.6×10^6 yr), ^{36}Cl(3.0×10^5 yr) and ^{129}I(1.6×10^7 yr) have already been measured with AMS in meteorites. Another cosmogenic radioisotope of particular interest in our laboratory is ^{60}Fe, where we have recently measured a new half-life value of 1.5×10^6 yr, substantially longer than previously thought ($\sim 3 \times 10^5$ yr). ^{60}Fe is expected to be present in meteorites at extremely low concentrations of ^{60}Fe/Fe $\sim 10^{-14}$. The major technical problem in an AMS measurement is the separation of the omni-present stable isobar ^{60}Ni from ^{60}Fe. Using 340-MeV ions from ATLAS and our newly-developed technique of isobar separation in a gas-filled magnetic spectrograph, we have measured ^{60}Fe in the iron meteorite Treysa for the first time (Fig. II-33). The ^{60}Fe/Fe value found[1] was $\sim 3 \times 10^{-14}$, consistent with the expectation.

Although our result demonstrated the feasibility of ^{60}Fe measurements at these very low concentrations in meteorites, the ^{60}Fe counting rate (~ one count per hour) is presently too low for systematic studies. This must await a substantial increase in beam current, such as expected from the ECR source and the new positive-ion injector of ATLAS.

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†The Hebrew University of Jerusalem, Jerusalem, Israel.
[1]W. Kutschera, Nucl. Instrum. Methods B17, 377 (1986).

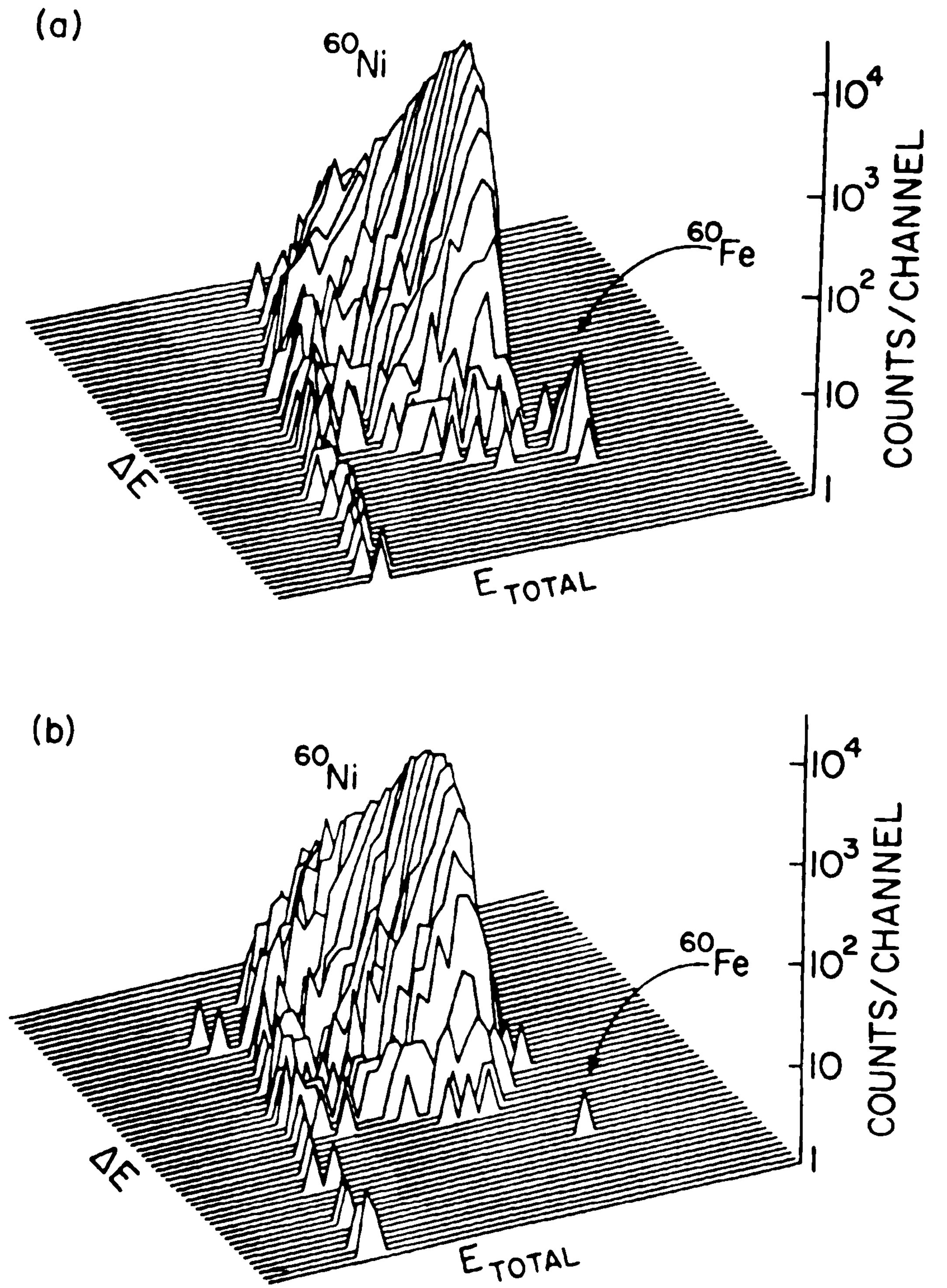

Fig. II-33. Mass-60 spectra measured with he gas-filled spectrograph in the focal-plane ionization chamber; (a) calibration sample with $^{60}Fe/Fe = 7 \times 10^{-12}$; (b) iron meteorite Treysa with $^{60}Fe/Fe \approx 3 \times 10^{-14}$. The isobar ratio of the mass-60 ions entering the spectrograph was $^{60}Ni/^{60}Fe \approx 10^8$ and 10^{10} for (a) and (b), respectively. Most of the ^{60}Ni ions are physically shielded from entering the focal-plane detector.

c. **^{41}Ca Concentration in Terrestrial Materials and Its Prospects for Dating of Pleistocene Samples** (W. Henning, W. A. Bell,* P. J. Billquist, B. G. Glagola, W. Kutschera, Z. Liu,† H. F. Lucas,‡ M. Paul, K. E. Rehm, and J. L. Yntema)

The major interest in ^{41}Ca ($t_{1/2}$ = 1.0 × 10^{5}yr) stems from its potential as a method of dating calcium-containing materials further back in time than is possible with ^{14}C ($t_{1/2}$ = 5730 yr). Particular interest arises from its prospects as a means of dating Middle and Late Pleistocene bone (about 100,000 to 700,000 years old) which contains significant amounts of calcium and is found at many sites of paleoanthropological interest. The ability to provide an isotopic method of assigning age directly to bone samples in this age range would clearly be of significance in clarifying uncertainties about chronological relationships among important fossil hominids for a time period during which major events in hominid biological and cultural evolution occurred. However, the natural ^{41}Ca/Ca concentration in terrestrial samples is expected to be very low, of the order of 10^{-14} or less. The long half-life of ^{41}Ca and its decay by electron-capture to the ground state of ^{41}K (with only soft X-rays and Auger electrons with energies of about 3 keV as detectable radiation) make decay counting not feasible. We have therefore used the highly-sensitive method of accelerator mass spectrometry in an attempt to detect ^{41}Ca at natural levels. Making use of pre-enrichment with an isotope separator, we were able to measure for the first time ^{41}Ca/Ca ratios in natural terrestrial samples.[1] For contemporary bovine bone we find a value of ^{41}Ca/Ca = (2.0±0.5) × 10^{-14}, and for limestone from two depths values of 3 and 8 × 10^{-15} were observed.

The AMS measurements were performed at ATLAS with ^{41}Ca ions of 200 MeV. Isobaric interference from ^{41}K was removed by choosing $^{41}CaH_3^-$ ions from the ion source ($^{41}KH_3^-$ is not a stable negative ion) and separating the remaining ^{41}K from ^{41}Ca in the gas-filled Enge split-pole spectrograph. Prior to the AMS measurements, the sample material was processed through a Calutron isotope separator at Oak Ridge National Laboratory, leading to a ^{41}Ca enrichment of about 150.

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‡Environmental Research Division, ANL.
§The Hebrew University of Jerusalem, Jerusalem, Isreal.
[1]W. Henning et al., Science 236, 725 (1987)

While the relatively-high ^{41}Ca concentration that we have found in contemporary bone is quite encouraging, this by no means yet assures that ^{41}Ca can be used as a dating tool. ^{41}Ca, like ^{14}C, is produced by cosmic-ray neutron secondaries. However, the bulk of the isotope is not made in the atmosphere, as is the case with ^{14}C, but rather in the upper meter of the soil profile by neutron capture on ^{40}Ca. What is needed in the future are systematic measurements to investigate the global distribution of ^{41}Ca. In such measurements one would certainly want to avoid the additional (costly) complication of isotope enrichment.

A straightforward approach to this problem is a substantial boost in ion-source output. Very encouraging results have been reported recently by Sharma and Middleton[2] who produced $^{40}CaH_3^-$ beams in the range from two to five microamps from freshly-prepared CaH_2 material. Such beam intensities would be sufficient for direct ^{41}Ca/Ca measurements. A different prospect evolves from the new positive-ion injector of ATLAS, currently under construction. The ECR source used in this new injector will produce very high intensities of multiply-charged Ca ions. However, it has to be seen how well one can handle the much stronger ^{41}K background associated with positive-ion production.

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[2]P. Sharma and R. Middleton, Proc. Fourth Int. Symp. on Acc. Mass Spectrometry, Niagara-on-the-Lake (1987), to be published.

d. <u>On the Measurement of ^{107}Ag/^{109}Ag Ratios in Meteorites</u> (W. Kutschera, T. Faestermann,* A. Gillitzer,* and G. Fortuna†)

It is generally believed that in the creation of elements in stars explosive nucleosynthesis plays an important role. Any fresh matter produced in this way should be rich in radioisotopes. Even if these radioisotopes completely decayed away over the age of the solar system, fingerprints of their primordial existence can be observed through the anomalous abundance of their stable decay products in early condensates of the solar nebula. Evidence for *in situ* decay has been found in certain meteoritic inclusions for the systems $^{129}I(t_{1/2} = 1.6 \times 10^7 \text{ yr}) \rightarrow {}^{129}Xe$, $^{26}Al(7.2 \times 10^5 \text{ yr}) \rightarrow {}^{26}Mg$ and $^{107}Pd(6.5 \times 10^6 \text{ yr}) \rightarrow {}^{107}Ag$.

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†Istituto Nazionale di Fisica Nucleare, Legnaro, Italy.

Very large ^{107}Ag excess has been observed by G. J. Wasserburg et al.[1] at Caltech in some iron meteorites which had Pd concentrations in the ppm range and Ag concentrations in the range from 0.01 to 1 ppb. Under this condition ^{107}Ag/^{109}Ag ratios as large as ten have been found compared to a solar system ratio of about one. The measurement of ^{107}Ag/^{109}Ag ratios with low-energy mass spectrometry requires the chemical extraction of picomole quantities of silver from the meteorite. Such a procedure has the inherent danger of affecting the original isotopic ratio through contamination with non-meteoritic silver and in addition averages over a rather large mass (about one gram). We have therefore performed AMS measurements at the Munich MP tandem with the goal to replace the "chemistry" with a direct ^{107}Ag/^{109}Ag ratio measurement of untreated meteoritic samples.[2]

Ag ions of 140 MeV were identified after tandem acceleration with a simple time-of-flight system consisting of a channel-plate start detector and a small CH_4-filled ionization chamber with a Si stop detector at a distance of 273 cm. Using an artifically-produced Ag tracer (^{105}Ag, $T_{1/2}$ = 41 d) a detection sensitivity of 7.5×10^{-5} ppb was found, comfortably below the expected concentration of stable Ag isotopes in meteorites. However, ^{107}Ag and ^{109}Ag could not be measured in the ppb range because of a persistent general Ag background in the ppm range. The cause of it is not clear, but could partly be due to the ion source itself. The lesson to be learned from this experience is that in order to measure stable isotopes of a relatively common element like silver one must probably work in a clean-room environment, which is difficult to establish at a non-dedicated accelerator facility.

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[1] G. J. Wasserburg, in Protostars and Planets II, D. C. Black and M. S. Mathews, ed. (University of Arizona Press 1985) p. 703.

[2] W. Kutschera et al., Proc. Workshop on Techniques in Accelerator Mass Spectrometry, eds. R. E. M. Hedges and E. T. Hall, Univ. of Oxford (1986) p. 139.

e. **Measurement of the $^{129}I/^{131}I$ Ratio in Chernobyl Fallout**

(W. Kutschera, D. Fink,* M. Paul,* G. Hollos,† and A. Kaufman†)

The reactor accident at Chernobyl on April 26, 1986 released a large variety of fission products into the environment. Since ratios of radioisotopes from the same element are not affected by the complicated processes governing release and transport, their measurement provides a rather direct information on the operating condition of a reactor, even at remote places. In particular, the ratio of a long-lived to a short-lived radioisotope allows one to make simple estimates about the total operating time of the reactor. The short-lived isotope will quickly reach equilibrium between production and decay, whereas the long-lived one builds up continuously as time goes on. At any given time the ratio of these isotopes will have a particular value. For a precise determination of the operating time, one would have to know the composition and geometry of the fuel material and include burnup of the fission products, but reasonably accurate estimates can be obtained without taking all this into account.

We have performed[1] a measurement of both he ^{131}I and ^{129}I content in a rainwater sample contaminated with fallout from the Chernobyl accident.

Rainwater collected in the area of Munich, West Germany, approximately one week after the reactor accident was investigated for its content of the fission products $^{129}I(t_{1/2} = 1.6 \times 10^7$ yr) and $^{131}I(8.04$ d). On May 6, 1986 a ^{131}I activity of 560 ± 80 Bq/liter (1 Bq = 1 decay per second) was measured with a Ge detector. The ^{129}I concentration in the water was measured with the AMS facility[2] of the pelletron tandem accelerator at the Weizmann Institute of Science in Rehovot, Isreal. A ^{129}I concentration of $(2.5 \pm 0.5) \times 10^{10}$ ^{129}I atoms/liter was found. From this we calculate for the time of release (assumed to be 26 April 1986) a $^{129}I/^{131}I$ ratio of 19±5.

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*The Hebrew University of Jerusalem, Jerusalem, Israel.
†The Weizmann Institute of Science, Rehovot, Israel.
[1]W. Kutschera et al., Proc. Adriatic Res. Conf. on Environmental Physics and Atmospheric Physics, Trieste 1986, Physica Scripta 35 1987, in press.
[2]D. Fink et al., Nucl. Instrum. Methods B5, 123 (1984).

From the measured $^{129}I/^{131}I$ ratio we calculate an operating time of the reactor between 1.5 and 2.3 years. This is in reasonable agreement with the actual operating time as reported by the Soviet expert delegation at the IAEA conference in Vienna, August 1986. Although natural ^{129}I is continuously produced by cosmic-ray spallation of Xe in the atomosphere and spontaneous fission of ^{238}U in the hydro- and litho-sphere, the anthropogenic input from reprocessing of spent nuclear fuel already exceeds the natural content by several orders of magnitude. Due to this condition and to the relative ease of detection with AMS (stable ^{129}Xe does not form negative ions), ^{129}I is likely to become one of the prime isotopes to trace anthropogenic influence on our environment.

f. **Measurement of the Half-life of ^{126}Sn** (W. Kutschera, I. Ahmad, P. Billquist, B. G. Glagola, K. J. Jensen, R. C. Pardo, K. E. Rehm and J. L. Yntema)

The half-life of ^{126}Sn, a low-yield fission product of ^{235}U and ^{239}Pu, has never been determined accurately. There exists only an estimate from the work of Dropesky and Orth[1] who give a value of approximately 1000,000 years. We have started an experiment with he goal to obtain a half-life value with at least 20% accuracy. This involves the measurement of the gamma-ray activity from the decay chain $^{126}Sn \rightarrow {}^{126}Sb \rightarrow {}^{126}Te$ and an AMS measurement of the ^{126}Sn content in the same material. After extensive chemical cleanup we isolated the tin fraction of a spent fuel-rod material from the Zion nuclear power plant (Illinois), which contains several nCi of ^{126}Sn. This material will be used to perform a new half-life measurement.

As usual, the AMS measurement has to deal with interferences from stable isobars. For a ^{126}Sn detection this means to efficiently eliminate ^{126}Te (^{126}Xe does not form negative ions and therefore is no problem for the tandem-injected ATLAS facility). The isobar separation was measured in a recent experiment with the stable isobar pair ^{124}Sn-^{124}Te. At 508 MeV energy supplied by the ATLAS booster linac a good separation was achieved using the gas-filled spectrograph technique (Fig. II-34). The next step will be to measure the $^{126}Sn/Sn$ ratio with this system. The sample material is expected

[1] B. J. Dropesky and C. J. Orth, J. Inorg. Nucl. Chem. 24, 1301 (1962).

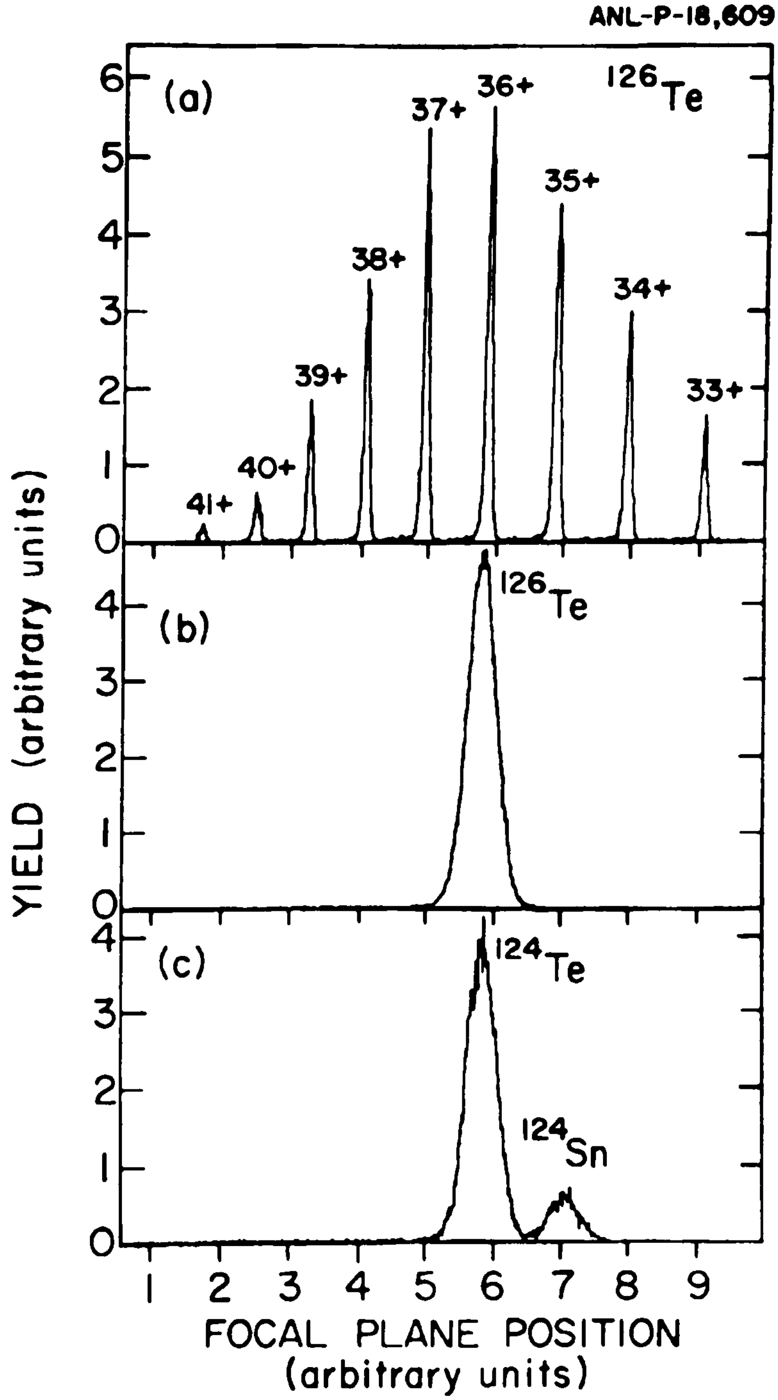

Fig. II-34. Demonstration of the effect of the gas-filled magnetic spectrograph on the separation of Sn-Te isobars. The yield of ions is plotted as a function of the position along the focal plane of the spectrograph. In (a) ^{126}Te ions of 508-MeV energy are dispersed by the different charge states they attain after passing through a 150-$\mu g/cm^2$ gold foil in front of the spectrograph. In (b) and (c) the spectrograph was filled with nitrogen gas of 8 torr pressure. In (b) the charge-state distribution of (a) collapsed into a single line. In (c) a pair of stable isobars, ^{124}Te-^{124}Sn, was accelerated and clearly separated due to their different mean charges in the gas.

to have a relatively high $^{126}Sn/Sn$ ratio of between 10^{-8} and 10^{-7}. It is also planned to attempt a measurement of the $^{121m}Sn/Sn$ ratio ion the same material. The gamma activity (37 keV) of this isomer has been observed and its relatively well-known half-life (55±5 yr) would allow an important check of the reliability of the ^{126}Sn measurement. However, the stable isobar interference from $^{126}Sb(Z=51)$ is more difficult to separate from $^{121m}Sn(Z=50)$ than $^{126}Te(Z=52)$ from $^{126}Sn(Z=50)$. It will be interesting to see how well the gas-filled spectrograph technique can handle this more difficult case.

E. OTHER TOPICS

In addition to the programs described above, selected topics in nuclear physics have been studied, involving various facilities in the Physics Division. This includes the measurement of the electron-capture decay branching ratio of ^{81m}Kr, of interest for a ^{81}Br solar-neutrino experiment; the calculation of the bound state beta-minus decay of completely-stripped $^{205}Tl^{81+}$ ions, the measurement of which would deliver the long-sought solar-neutrino capture cross section on ^{205}Tl-containing ores; investigations on triaxiality and reflection asymmetry in ^{225}Ra and the mass-220 region; exploration studies about the possibility of a condensed crystalline state in heavy-ion beams; and the search for positron resonances in the interaction of positrons with electrons.

a. **Electron-Capture Decay Branching Ratio of ^{81m}Kr** (C. Davids, T. F. Wang, I. Ahmad, R. V. F. Janssens, R. Holzmann, and A. Konstantaras)

^{81}Br has been proposed as a detector of solar neutrinos. Such a detector would be predominantly sensitive to neutrinos coming from the decay of ^{7}Be in the sun. In order to assess the feasibility of ^{81}Br as a solar-neutrino detector, it is necessary to know the rate of neutrino capture leading to ^{81}Kr. The matrix element for neutrino capture is the same as for the inverse process of electron capture, apart from spin factors.

The rate of neutrino capture to the ^{81}Kr ground state is far too slow to make a practical solar-neutrino detector. However, there is an isomeric state in ^{81}Kr at 190 keV which has the correct quantum numbers to provide a reasonable rate of neutrino captures from the ^{81}Br ground state. If the electron-capture decay rate of this isomer were known, the neutrino-capture rate to this state could then be determined. A group at Princeton measured the electron-capture rate in 1981. Our assessment of their result, based on known transition rates in nearby nuclei, suggests that it is incorrect, yielding too large a neutrino-capture rate.

We have measured the electron-capture decay branching ratio of the 190-keV state in ^{81}Kr by observing the resulting Br K X-rays following the decay. Figure II-35 shows a schematic diagram of the apparatus. A radiopharmaceutical ^{81}Rb-^{81m}Kr generator served as a source of the isomer, and in order to reduce the background, the X-rays were observed in anti-coincidence with conversion electrons and Compton-scattered 190-keV gamma rays. The resulting branching ratio of $(3.14 \pm 0.58) \times 10^{-5}$ leads to a log ft for the neutrino capture from ^{81}Br to the 190-keV state in ^{81}Kr of $5.10^{+0.06}_{-0.07}$. This gives a capture rate nearly a factor of 2 slower than that calculated from the earlier Princeton data. A recent remeasurement of this quantity by the Princeton group confirms our result. The implications for a potential ^{81}Br solar-neutrino detector are that it is still practical, although the calculated rate is now somewhat less than expected.

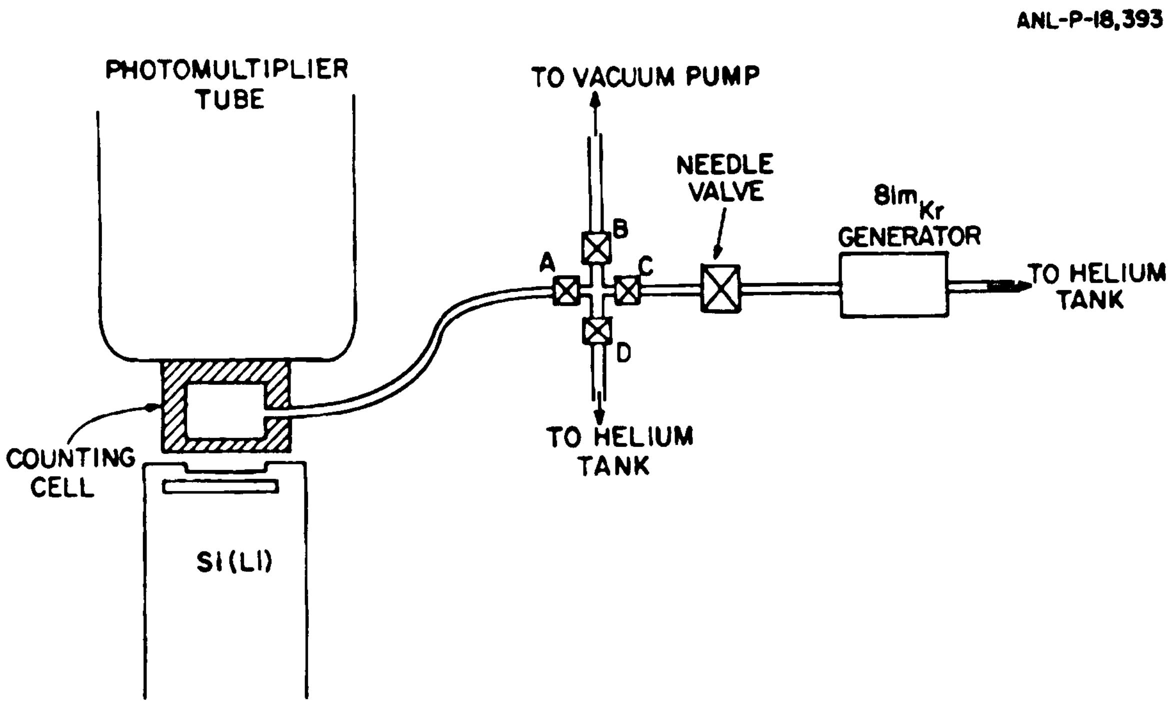

Fig. II-35. Schematic diagram of apparatus used to measure ^{81m}Kr electron capture branching ratio.

b. **Bound-State Beta-Minus Decay of Completely-Stripped $^{205}Tl^{81+}$ Ions to Hydrogenic $^{205}Pb^{81+}$ Ions and Its Application to Solar-Neutrino Detection** (M. S. Freedman)

A dominant uncertainty in the proposed measurement of the low-energy component of the solar neutrino flux by neutrino capture in a ^{205}Tl-containing mineral is the interaction cross section to form the $1/2^-$ state at 2.3 keV excitation energy in ^{205}Pb from the $1/2^+$ ground state in ^{205}Tl. The cross section is given by the rate of any weak-interaction process connecting these nuclear states. Thus far nuclear theory cannot consistently or reliably calculate this or several other quasi-analogous beta-decay rates in the near-doubly-magic region to better than ±50%, and direct measurement of either the neutrino capture rate or its inverse, electron-capture decay of the $1/2^-$ state of ^{205}Pb, is not remotely possible.

A new technique recently proposed by P. Kienle from GSI Darmstadt involves inducing a normally energetically- (by 40 keV) forbidden β^- decay from the $1/2^+$ ground state of ^{205}Tl to the $1/2^-$ excited state of ^{205}Pb. Completely-stripped $^{205}Tl^{81+}$ ions, maintained in this state for substantial times as circulating beam in a heavy-ion storage ring such as is proposed at GSI, are energetically unstable via bound-state β^- decay to hydrogenic $^{205}Pb^{81+}$ with one K electron, owing to the availability of the 101.5-keV 1s electron binding energy in $^{205}Pb^{81+}$. Measuring the rate of this decay determines the nuclear matrix element sum governing neutrino capture in ^{205}Tl. Three approaches to the estimation of the rate of this decay showed that with $^{205}Tl^{81+}$ ions in the order of 10**9 stored in the ring, one would expect about 10**4 decays per hour. Therefore, after a few hours of storage, a quantitative separation of the accumulated $^{205}Pb^{81+}$ ions from the primary beam should be possible resulting in a measurement of the desired quantity.

The rate turns out to be very sensitive to the ^{205}Tl-^{205}Pb mass difference, which must be known to within 1 keV. Several experiments to refine this value are considered: mass spectrometry of the doublet pairs $^{205}Tl^{35}Cl$-$^{203}Tl^{37}Cl$ and $^{203}Tl^{37}Cl$-$^{205}Pb^{35}Cl$; Q value of the ^{205}Tl(^{3}He,t)^{205}Pb reaction; Q_{EC} of the ^{205}Pb($5/2^-$ g.s.) to ^{205}Tl($1/2^+$ g.s.) decay; and Q_β of the ^{206}Tl to ^{206}Pb decay.

c. **Additional Information on Intrinsic Reflection Asymmetry in ^{225}Ra** (I. Ahmad, R. G. Helmer,* M. A. Lee,* and C. W. Reich*)

A detailed study of the levels in ^{225}Ra has been carried out in order to provide additional data to test the octupole deformation model. Measurements included α-spectroscopy with a magnetic spectrometer, elctron spectroscopy with a Si detector, and γ-ray singles and γ-γ and γ-α coincidence measurements. From the results of these measurements a comprehensive level scheme consisiting of 22 levels was constructed. The ground-state band has been identified up to spin 13/2 ℏ. It is found necessary to include an additional alternating term (B_1) in the rotational energy formula to adequately fit the energy spacings in the ground ($K\pi$ = 1/2+) and $K\pi$ = 1/2- bands as +1.89 and -2.56, respectively. This analysis gives the decoupling parameters for the 1/2+ and 1/2- bands. These are closer to each other than the previously deduced values and hence give additional support to the presence of octupole deformation in ^{225}Ra.

*Idaho National Engineering Laboratory, Idaho Falls, Idaho.

d. **Triaxiality and Reflection Asymmetry in the Mass-220 Region** (I. Ahmad and R. R. Chasman)

The octupole-deformation model has been fairly susccessful in describing many properties of odd-mass Ra and Ac nuclei in the A = 221-229 range. However, there still remain some disagreements between theory and experiment. One is the rotational energies of the band members and the other is the large interband E2 transition rates. Both of these could arise from triaxiality in the shape. We have explored the presence of gamma softness in ^{223}Ra and ^{225}Ra. Level lifetimes were measured, which in conjunction with the previously-known level schemes and γ-ray branching ratios, provided B(E2) values. Using these interband B(E2) values and the rotational B(E2) values we deduced the gamma deformation. We find gamma deformation of 12 degrees in these nuclei which clearly indicates that these nuclei are gamma soft or gamma deformed.

e. **Exploration of the Possibility of a Condensed Crystalline State in Heavy-Ion Beams** (J. P. Schiffer, and A. Rahman*)

Storage rings for heavy ions, presently under construction, will allow the particle beams to be cooled to very low temperatures. In an attempt to understand the possible phenomena that take place under such conditions, molecular dynamics calculations have been carried out on the Energy Research Cray B. The first calculations were carried out approximating the beam optics by assuming focussing forces to be constant in time, and neglecting the effects of rotation. The surprising result emerged that under such circumstances the beam arranges itself in concentric shells with the particles in each shell arranged in a hexagonal pattern characteristic of two-dimensional order. Yet the overall correlation between particles shows nearest neighbors with a coordination characteristic of a bcc solid. The coexistence of the two symmetries is not fully understood. The innermost cylinder in this array seems to have a preference for a helical arrangement of particles.

Whether such an arrangement of particles may indeed be achieved in the storage ring depends on a number of factors. Some of these, such as the effects of the shear induced by rotation are just beginning to be explored. Others, such as periodic focusing forces and particular arrangement of cooling sections will have to be investigated in the future. The possibility of carrying out real experiments to search for such systems is being investigated. Such plans must of course await the operation of the storage rings 2-3 years from now.

*University of Minnesota, Minneapolis, MN.

f. **Search for Positron Resonances in the Interaction of Positrons with Electrons** (I. Ahmad, S. J. Freedman, R. V. F. Janssens, J. P. Schiffer, and T. F. Wang)

Reports from GSI about sharp positron lines from collisions between uranium or other heavy nuclei continue to persist. With the completion of the ATLAS uranium upgrade still some time off in the future it is important to investigate the possibility by other techniques that this phenomenon might conceivably be the consequence of a neutral resonance which decays into an electron-positron pair. Such a resonance may then be observable in low-energy

$e^+ - e^-$ scattering experiments. We had started some measurements last year, using positrons of sufficient energy to make a resonant state with total mass of 1.7 MeV on free (or lightly bound) electrons, and the results were negative.

Recently there has been a published report that with a source of ^{68}Ge-^{68}Ga (whose decay does not provide sufficent positron energies to make such a resonance on free electrons), a Th scattering foil, and two mini-orange spectrometers viewing the scatterer with an angle of separation of 90 degrees, a line has been observed that roughly matches the characteristics of the GSI data. It is perhaps possible that with a bound electron (a Th scatterer was used) such a resonance might be formed. We attempted a similar measurement, using two mini-orange electron spectrometers viewing a source and scatterer from opposite sides (180 degrees apart). No evidence for a line has been seen up to this time.

F. EQUIPMENT DEVELOPMENT AT THE ATLAS FACILITY

The initial phase of development of equipment for the ATLAS expeprimental system was completed in FY 1986 with the full commissioning for use of the large scattering facility, the split-pole spectrograph, the first phase of the BGO sum-energy/multiplicity filter with a ring of Compton-suppressed detectors, and major elements of the beam-line system. The second phase of the BGO ball, bringing it to the full complement of 50 BGO crystals and 12 Compton-suppressed detectors, is under way and will be completed in 1987. Other activities in this year include a start on development work for a Fragment Mass Analyzer. In other respects the equipment effort is aimed at adapting these major facilities to particular classes of development. Several smaller scattering chambers are being constructed in order to use elements of, the BGO system in coincidence experiments with charged particles. New detectors are being developed for both the large scattering chamber and the spectrograph, with improved timing and energy resolutions and permitting larger solid angles. The VAX 750 utilizing the DAPHNE data-analysis system is now in full use at ATLAS.

a. **Proposal for a Fragment Mass Analyzer** (C. N. Davids, W. F. Henning, I. Ahmad, B. B. Back, R. R. Betts, L. M. Bollinger, J. Falout, R. V. F. Janssens, D. G. Kovar, T. L. Khoo, B. Nardi, K. E. Rehm, S. J. Sanders, and J. P. Schiffer)

A proposal has been prepared for constructing a large-acceptance Fragment Mass Analyzer (FMA) at ATLAS. This device will be used to separate nuclear reaction products from the beam and transport them to a detector station at the focal plane. Since the ions will be dispersed in M/Q (mass/charge), measurements of position, energy, and energy loss will enable the nucleon number A and proton number Z of the particles to be determined. The solid angle of the FMA will be exceptionally large, approximately 10 msr, and a large range of energies and masses will be simultaneously accepted. The properties of the FMA are well suited to the beams available from ATLAS currently and in the future.

The versatility of the FMA permits it to be used in a wide variety of scientific applications. Its high transmission makes it an ideal tool to search for suprheavy elements. Both neutron-deficient and neutron-rich nuclei far from stability can be produced and separated in numbers sufficient to enable their masses to be measured. With the FMA serving as a mass filter in coincidence with detectors at the target position, an entirely new class of experiments becomes possible, aimed at the study of weak nuclear reaction channels. The FMA can be effectively used in the investigation of many types of nuclear reactions, including quasielastic scattering and transfer reactions near the Coulomb barrier.

Figure II-36 shows a schematic layout of the proposed FMA. While the distance between the target and the first quadrupole is currently fixed at 30 cm, the focal plane can be located anywhere within about 1 meter of the last electrostatic dipole. There is room at the target position to place 8 Compton-suppressed germanium spectrometers, plus much of the BGO array. Figure II-37 shows the placement of the FMA in Target Area III of ATLAS.

It is expected that a number of ATLAS users will become involved in the FMA project. During the design stage, currently going on, users will be asked to provide input on the target chambers and the types of detectors

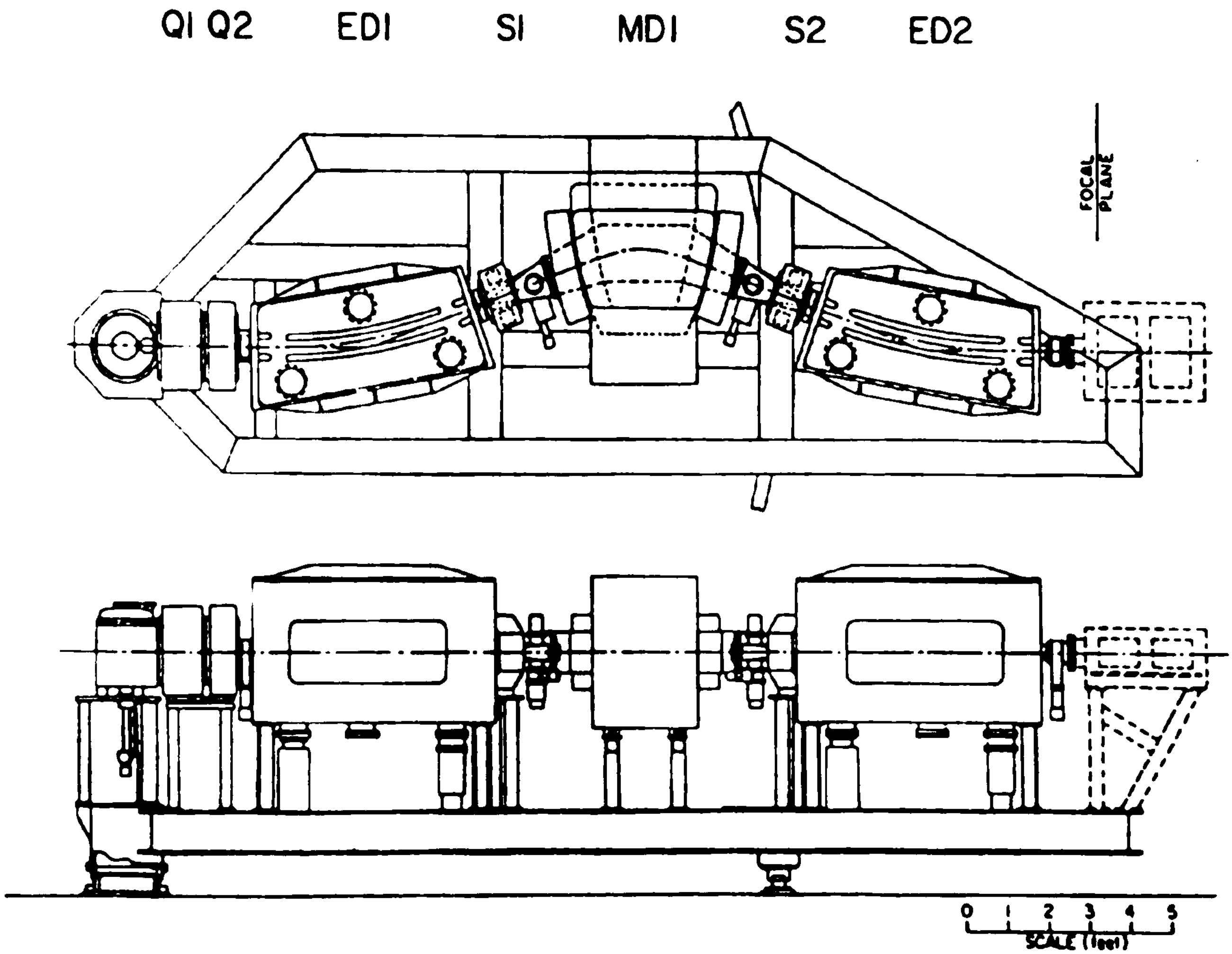

Fig. II-36. Schematic layout of the proposed Fragment Mass Analyzer.

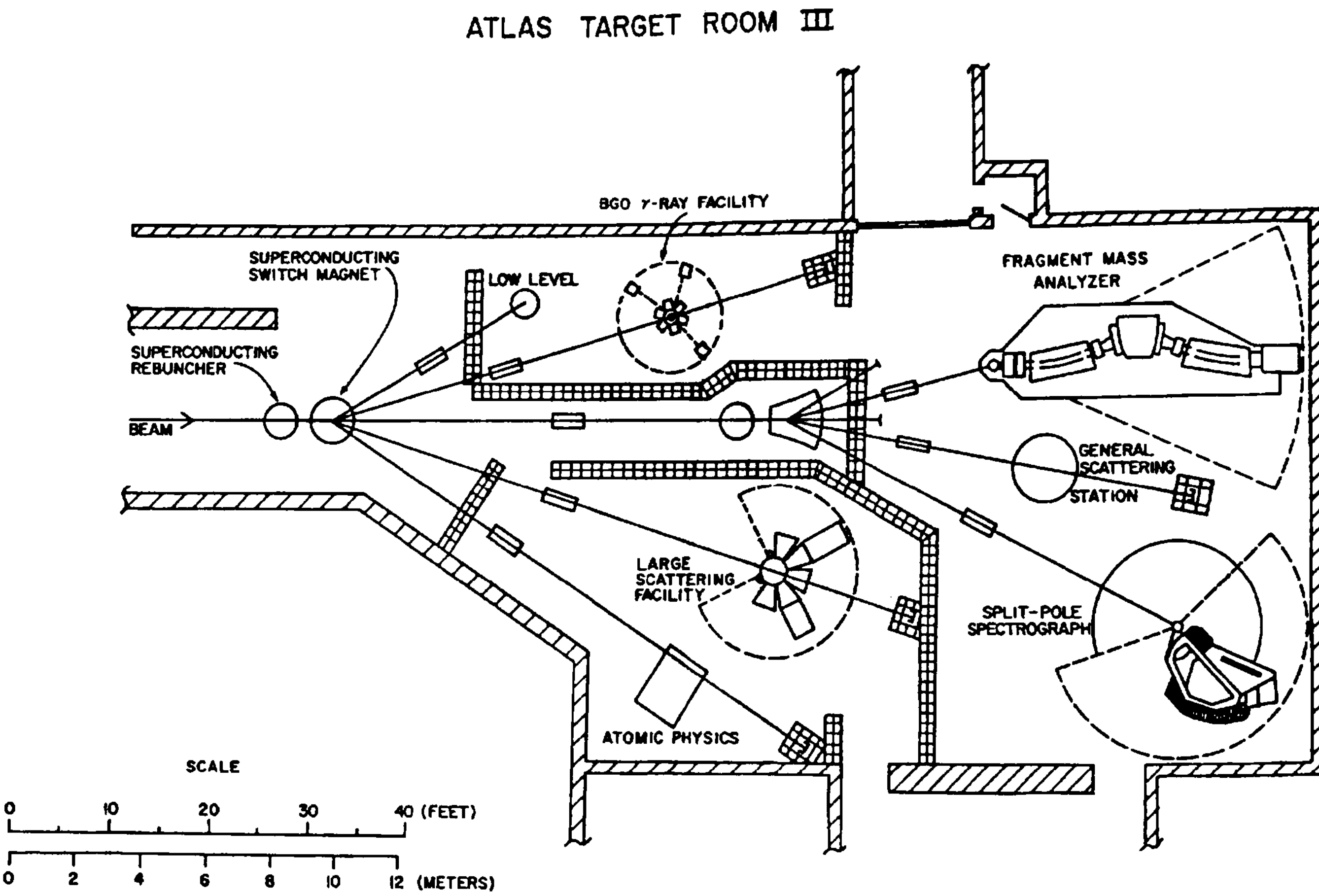

Fig. II-37. Location of proposed Fragment Mass Analyzer in ATLAS Target Area III.

needed for proposed experiments on the FMA. Once these two areas are finalized, users will be asked to help in their construction or to provide specialized detectors, such as neutron arrays.

We have received approval for the FMA project this year. Tasks to be accomplished in the first year are: development and testing of the high-voltage supplies for the electrostatic dipoles, finalizing the optics design, and completion of the engineering design of the FMA components. When this stage is reached, the support structure can be designed and constructed. The procurement process for the main FMA components and the vacuum system will take place in 1988. At this time, engineering design can begin on the target chambers and detector station, followed by fabrication. All FMA components should be received by the beginning of 1989, and assembly and operational testing of the system as a whole will begin. The first experiments using the FMA are expected to be performed sometime in mid-1989.

b. **Design Calculations for a Fragment Mass Analyzer** (C. Davids, W. Henning, Z. Liu)

As part of the preparation of a proposal for construction of a Fragment Mass Analyzer (FMA), beam-optics calculations using the MIT program RAYTRACE have been performed. The basis for the design was the Recoil Mass Spectrometer presently being built at the Laboratori Nazionali de Legnaro (LNL) in Padova, Italy.

This device utilizes a quadrupole doublet as an initial focusing element, followed by a symmetric combination of electrostatic dipole, magnetic dipole, and electrostatic dipole. Sextupoles preceding and following the magnetic dipole are used, along with curved-magnet pole tips, to provide second-order corrections. These rotate the focal plane to a position perpendicular to the optical axis and also reduce the second-order energy-dependent displacement. The separation of the dipole elements is adjusted to produce an energy-dispersionless focus at the detector plane. This is illustrated in Fig. II-38, which shows how the trajectories of particles with the same mass but differing energies are brought together at the focal plane.

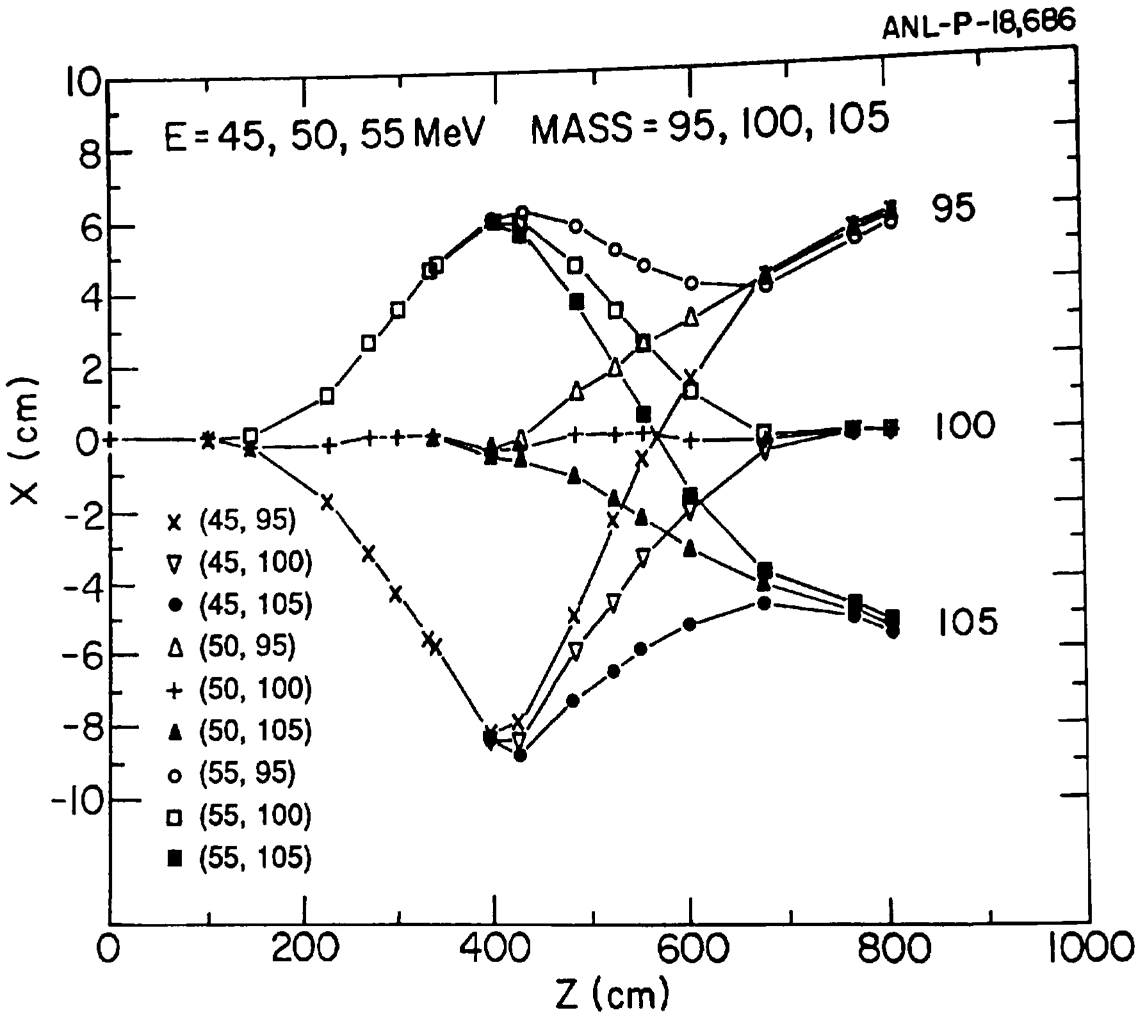

Fig. II-38. Calculated trajectories of mass 95, 100 and 105 particles with energies 45, 50, and 55 MeV, incident along central ray of the FMA.

The resulting device is approximately 8 meters in length, and has large (≈ 10 msr) solid-angle acceptance. It can transmit particles in an energy range of ±20%, with a simultaneous mass (actually M/Q) range of ±5%. The mass resolution is typically 1/280 for operating conditions of 5 msr solid angle and ±10% energy range.

One of the most outstanding features of the proposed FMA is its ability to make energy measurements using time of flight. The time dispersion of the FMA is <0.05% for particles of the same mass and energy, providing an excellent match with the pulsed-beam properties of the ATLAS accelerator (100–150 ps burst width). Energy measurements with a presicison of 0.1% can thus be made if the mass of the particle is determined, for instance by its position on the FMA focal plane.

Considerable time has been spent in investigating variations in the original optical design, with the aim of improving the performance of the device. Among these are: a) using multipole lenses in place of the sextupoles to provide adjustable octupole corrections, b) reducing the effective length of the first quadrupole by 33% in order to increase the angular acceptance in the vertical direction, and c) halving the target-to-first-quadrupole distance in order to increase the angular acceptance in the vertical direction. Each of these changes produces some improvement in the desired direction, but are either costly in terms of resources or produce a compensating loss in some other parameter.

The results of these calculations indicate that the design developed for the FMA contains a number of performance compromises, but appears to be close to the optimum in terms of a general-purpose instrument.

c. Development of Vacuum-Mounted High-Voltage Supplies for the FMA (C. Davids and W. Kutschera)

The development of vacuum-mounted high-voltage power supplies for the electrostatic dipoles of the Fragment Mass Analyzer (FMA) has begun. Instead of using four external 300-kV air- or oil-insulated power supplies, the approach used in powering the electrostatic plates of the MIT-ORNL Velocity Filter will be adopted. In this configuration, the high-voltage multiplier and filter stack is separated from the RF driver electronics and is mounted in an insulating container inside the electrostatic dipole vacuum chamber. Filling this container with mineral oil allows its dimensions to be reduced considerably over what would be needed if air insulation were used. The high-voltage connection is made by direct contact between the electrode and the output of the rectifier-filter stack. Also included in the oil-filled container is a resistive voltage divider, which provides both a method of measuring the high voltage and a feedback signal for the driver electronics. In this way, a voltage stability of <0.01% should be attained.

There are several advantages to using the vacuum-mounted configuration. The first is that complicated high-voltage vacuum feedthroughs are no longer required. Secondly, this means that damping resistors, high-voltage coaxial cables, and their attendant energy-storing capacitances are also eliminated. Because of this, and the inherent low energy stored in the power supply itself, damage suffered by the electrodes during sparking is kept to a minimum. In fact, since the high voltage is conducted directly to the electrode without exposure to air or vacuum, the risk of arcing is expected to be primarily confined to inter-electrode sparks.

Two prototypes will be constructed, one of each polarity. After off-line tests of vacuum and voltage capabilities, the power supplies will be used to power some mock electrodes in the ATLAS 36-inch scattering chamber. Here they will be subjected to bombardment by the heavy-ion beam from the ATLAS accelerator, in order to closely simulate the effect of dumping the beam on the positive electrode of the first electrostatic dipole in the FMA.

d. **Construction of a Gamma-ray Facility for ATLAS** (R. V. F. Janssens, T. L. Khoo, R. Holzmann, U. Garg,* M. W. Drigert,* K. Beard,* J. J. Kolata,* and P. Wilt*)

A gamma-ray facility, which will ultimately consist of (a) a 4π gamma-sum/multiplicity spectrometer with 50-56 hexagonal BGO elements and (b) 12 Compton-Suppressed Ge detectors (CSG) external to the hexagonal elements is currently under construction. The instrument is expected to have a powerful impact on a large class of experiments in heavy-ion research ranging from γ-ray spectroscopy studies of great detail to the investigation of reaction mechanisms.

Phase I of the project was completed at the end of 1985. It consists of 14 elements of the inner array and 7 CSG's. This setup has been used successfully in many experiments. Meanwhile, work has continued on phase II and it is expected that the system will be completed by the end of 1987.

During the last year much effort was devoted to the following activities:

-- All detectors for the array have been ordered. During the year the design of the detectors for the outer ring was completed. Discussions with the manufacturer on these detectors and on the hexagonal detectors with special holes (to allow γ rays to reach the CSG's) were conducted and resulted in a final design. Manufacturing is now under way.

-- All electronics modules for the array which are not available commercially have been designed and prototypes have been tested. The actual construction of all the units is well underway. This activity is performed at the University of Notre Dame.

-- An 8th CSG was installed and used in several experiments.

-- Orders have been placed for the remaining 4 CSG's (i.e. BGO shields and Ge detectors) and the accompanying electronics.

*University of Notre Dame, South Bend, IN.

-- Several modifications and improvements were performed to the automatic liquid-nitrogen filling system for the Ge detectors.

-- Equipment has been installed that will allow maintenance of the Ge detectors (pumping on the cryostats and repair for neutron damage).

-- Several new target chambers were built. In addition to the original chamber where the beam is stopped in the target or in a stopper foil immediately thereafter, provisions now exist to dump the beam downstream from the target location. In collaboration with Prof. R. Kozub (Tennessee Tech. Univ.) a small chamber that can hold several particle ΔE-E telescopes (while still fitting in the small space available within the array) was also built.

-- Design work has started on a much more elaborate chamber for charged-particle--γ-coincidence studies (see section II.F.d. in this report.)

e. **Scattering Chamber for the Argonne-Notre Dame γ-Ray Facility**
(S. J. Sanders J. Falout, R. V. F. Janssens, and T. L. Khoo)

Work has begun on the design of a general-purpose scattering chamber to be used in conjunction with the γ-ray facility at Argonne. During the past year a number of studies at Argonne have employed particle-γ coincidences with the particle identification used to select reaction channels for spectroscopic investigation. Although these experiments have, in general, been quite successful, the small size of the present particle scattering chamber (about 5" in diameter) makes it impossible to measure high-quality particle spectra in coincidence with γ rays. Particle-γ experiments which require particle time-of-flight determination with good angular resolution are now being planned for ATLAS and to satisfy the requirements of these next-generation experiments we are designing a large, wedge-shaped chamber (Fig. II-39) which will flare out from the target position and allow particle flight paths of greater than 70 cm. The basic vacuum enclosure will be completed by summer 1987, and the entire chamber should be completed by the end of 1987.

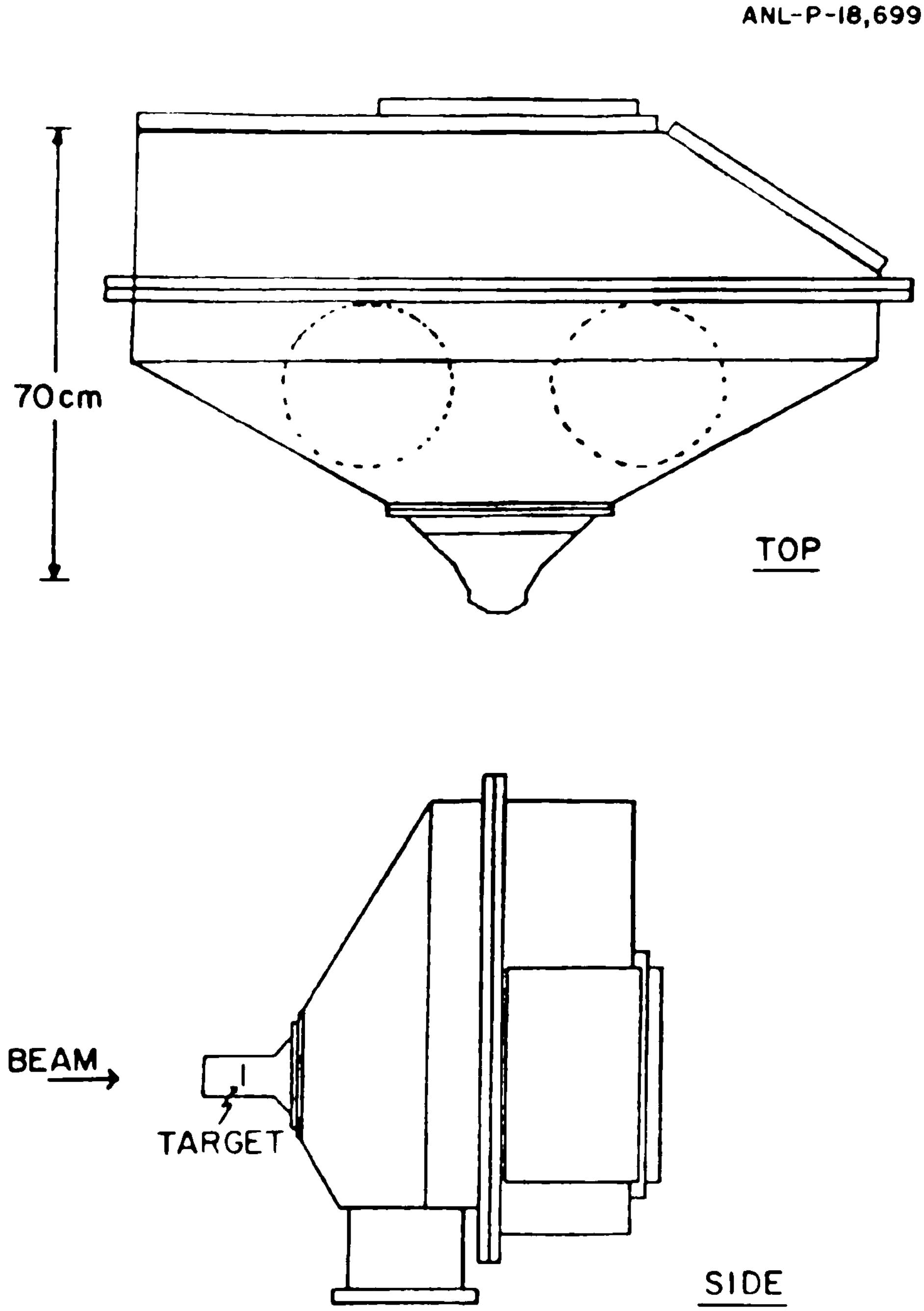

Fig. II-39. Top and side views of the particle scattering chamber under construction for the γ-ray facility.

f. **ATLAS Scattering Chamber Facility** (D. G. Kovar, J. Falout, and B. Nardi)

The ATLAS scattering chamber came into operation in the previous year. During the last year the chamber has been used extensively to perform a wide variety of measurements. All aspects of the chamber operation have been found to meet or exceed the design expectation. Effort has been spent to expand the chamber's capabilities and improve the ease and efficiency of making measurements in the chamber. Internal hardware for mounting a wide variety of detector systems (including long flight-path arms) have been fabricated. Capabilities for mounting NaI(Tl) detectors (both in and out of the reaction plane) on the internal rings or on the chamber ports have been provided. Provisions for multi-gas detector systems have been installed. Sufficient power and cabling to handle large experimental setups have been provided. Provision for target transfer into the chamber under vacuum now exists and has been used. Effort has been spent in developing, together with the accelerator staff, the good timing characteristics of the ATLAS beams in order to utilize this in time-of-flight measurements. Future plans include the purchase of dedicated electronics to make more efficient the setup and running of the more complex experimental configurations, and the development of detector systems which can be easily coupled to the chamber. These detector systems should utilize the uniqueness of the ATLAS beams and the flexibility of the chamber's design.

g. **Design of a New Scattering Chamber for Particle-gamma Coincidence Studies** (K. E. Rehm and J. Goral)

We have started the design of a new scattering chamber for the split-pole spectrograph which would allow particle-gamma coincidence studies with good particle separation. This new scattering chamber would allow use of at least five Compton-suppressed Ge-detectors from the BGO setup very close to the target. The spectrograph will be used as a high-resolution particle detector for identification of the outgoing particles. This new setup, which combines the advantage of gamma and particle detection, will permit studies of the interpaly between transfer and Coulomb excitation in heavy-ion reactions with much better particle separation than done so far.

h. **Detector Development Laboratory** (B. D. Wilkins and D. J. Henderson)

During the year, significant progress has been made on two different detectors; a low-pressure multiwire gas avalanche detector and a large-area Bragg-curve spectrometer Each of these projects is discussed separately elsewhere in this report.

A third project which has made significant progress this year is the design, construction, and development of a small-area microchannel plate detector with good timing (< 100 picoseconds) and position information. Construction on this detector is finished and testing of the detector is currently under way using an alpha source to optimize the position and time resolutions. Initially only one dimension of position will be obtained. If the technique works well it can be modified fairly easily to obtain both x and y information. In the future when timing resolutions of <100 picoseconds is essential, large-area channel plates with x and y position information show high promise. The development work on this detector is the first step in this direction.

i. **A New Configuration for a Low-pressure Multiwire Avalanche Detector** (B. Wilkins, D. Henderson D. G. Kovar, C. Beck, B. G. Glagola, and T. -F. Wang)

A fast two-stage, multiwire gas counter (Breskin type) was used in a number of experiments this past year at ATLAS. The results from this detector, although usable, were somewhat disappointing with the timing characteristics never reliably better than ~300 picosec for heavy ions.

A new configuration for this detector has recently been tested at ATLAS with heavy ions. The central wire-grid structure (anode) of the Breskin design has been replaced by a thin film (metallized on both sides) and powered as the cathode. Results look very encouraging. With this new design, timing resolutions of 150-200 picosec were achieved with heavy ions. Use of this newly configured large-area detector in time-of-flight systems will provide a substantial improvement in the expected mass resolution.

j. **Development Work on a Large Bragg-curve Spectrometer** (B. Wilkins, D. Henderson, D. G. Kovar, C. Beck, and B. G. Glagola)

The Bragg-Curve Spectrometer (BCS) has been developed as part of a large-area time-of-flight system for use at the scattering facility at ATLAS. Initial tests on this detector using heavy-ion beams from ATLAS produced energy resolutions of <0.8% with excellent Z resolutions ($Z/\Delta Z=80$) for projectile-like fragments (10 MeV/A) near Ni. Further tests have been carried out this year to determine the resolution of the BCS for particles which have insufficient energy to achieve their Bragg peak in the detector. Bench-top tests using fission fragments from a ^{252}Cf (spontaneous fission) source and beam-line tests using heavy ions from ATLAS (^{32}S) have been used on this detector to determine its energy and Z resolution for low-energy evaporation residues and fission fragments. Good Z resolutions for $Z < 30$ are achieved down to energies of ~ 1 MeV/A. A new electronic technique is being developed, which may extend the region of good resolution to lower energies and higher Z.

k. **Development of a New Focal-plane Detector for the Split-pole Spectrograph** (K. E. Rehm and F. L H. Wolfs)

The availability of heavier projectiles from the ATLAS accelerator made it necessary to develop a new focal-plane detector with good particle separation both in mass and charge even for particles in the $A \approx 100$ region. Based on our good experience with a parallel-plate avalanche timing counter (PPAC) we have built a 50-cm-long position-sensitive PPAC. The position information is obtained from 10-μ-thick tungsten wires spaced 1-mm apart which are read out by integrated delay lines. In various tests, the linearity, efficiency and the count-rate behavior of this detector has been tested with various particles ranging from ^{4}He to ^{58}Ni. The measured intrinsic time and position resolution was 200 psec and 0.8 mm, respectively. The detector has been used in various experiments involving count rates up to 20 KHz.

For energy and Z-determination a Bragg-curve detector has been built which will be mounted behind the PPAC. Tests with heavy-ion beams for this detector are planned for the spring of 1987.

ℓ. **Development of NaI(Tl) Charged-particle Detectors** (C. Davids, D. Kovar, C. Beck, M. Vineyard, A. Konstantaras, C. Maguire,* F. Prosser,† V. Reinert,† K. Kwiatkowsky,‡ J. Kolata§)

The thin front-window NaI(Tl) detectors have proved to be quite versatile in experiments where it is necessary to detect and identify large numbers of light charged particles associated with fusion reactions. The detector response to different light particles have been studied. In a run at the Indiana Cyclotron, protons up to 100 MeV and alpha particles with energies greater than 150 MeV were used to obtain energy calibration information. Figure II-40 shows the combined results of runs at ATLAS, Notre Dame and Indiana for protons over a wide energy range. The 5 recently-acquired 2" dia. x 2" deep detectors utilize Hamamatsu R329 photomultipliers (equivalent to the RCA 8575), and new vacuum-compatible bases for these tubes have been developed.

Some insight has been obtained into the mechanism whereby the pulse shapes are different for different species of ions. It appears that the scintillation pulse shapes for the shortest range and most highly-ionizing particles closely resemble a pure exponential decay with a time constant of 250 ns, while those or gamma rays and longer-range charged particles have a relatively constant portion at the beginning of the pulse, followed by the exponential decay. New electronic methods of achieving pulse-shape analysis are being worked out. One such scheme uses a charge-integrating analog-to-digital converter, and promises to be the most economical method where large numbers of detectors are involved. These studies will continue to be pursued using a high-energy ^{16}O beam from ATLAS.

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†University of Kansas, Lawrence, KS.
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§University of Notre Dame, Notre Dame, IN.

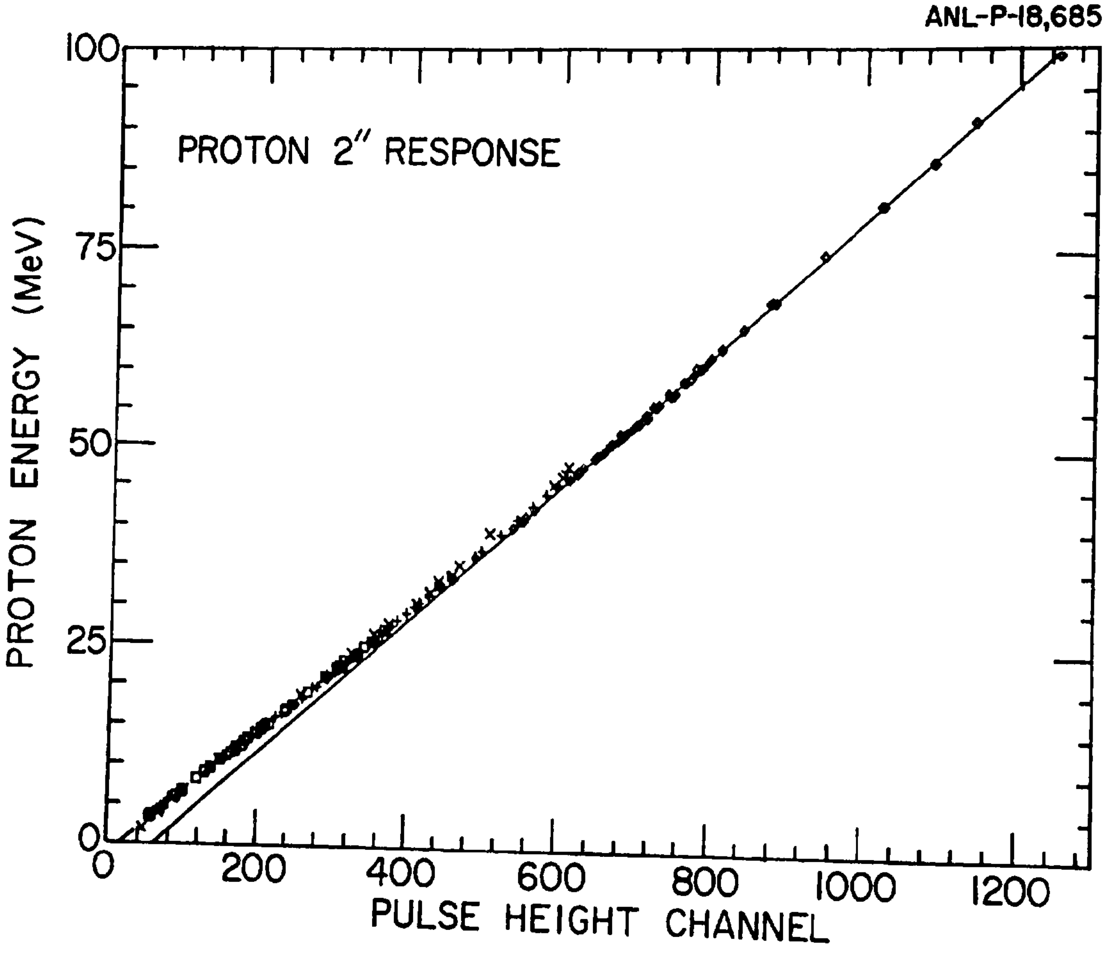

Fig. II-40. Proton energy-light output for 2" NaI(Tl) detector. Solid curve is linear least-squares fit to higher energy points.

m. **Superconducting Solenoid Lens Electron Spectrometer** (P. J. Daly,* Z. W. Grabowski,* W. Trzaska,* R. V. F. Janssens, and T. L. Khoo)

Work has continued on the construction of the Purdue superconducting electron spectrometer to be installed at ATLAS. Following the design sutdies of the spectrometer assembly, construction and final assembly has taken place at Purdue Vacuum and detector testing have also been performed and minor problems have been corrected. The spectrometer has been installed at the 6-MV tandem facility of Purdue University for initial tests of all systems.

First electron spectra were obtained, showing that all components (solenoid and detectors) meet the specifications. Several baffles for delta rays and for positrons were constructed and first tests have been conducted.

In view of the large demand for beam time at ATLAS, it was felt that as many tests as possible should be performed at Purdue where beam time is more easily available. Completion of the measurements is scheduled for the spring of 1987. A first measurement with ^{64}Ni beams at ATLAS is scheduled for the summer of 1987.

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n. **^{18}O-induced Transfer Reactions Studied with a Superconducting Solenoid Spectrometer** (R. L. Stern,* F. D. Becchetti,* J. W. Janecke,* P. M. Lister,* D. G. Kovar, R. V. F. Janssens, M. F. Vineyard, W. R. Phillips, and J. J. Kolata†)

We have studied ^{18}O-induced transfer reactions on neutron-rich targets, with the goal of measuring the masses of very neutron-rich nuclei produced via the (^{18}O,^{18}Ne) and (^{18}O,^{20}Ne) reactions. Our experiments used a 106-MeV ^{18}O beam incident on ^{26}Mg and Ni^{19}O targets and a 100-MeV ^{18}O beam on ^{26}Mg and ^{110}Pd targets. The University of Michigan air-core superconducting solenoid spectrometer[1-4] was used to focus reaction products near zero degrees (θ = 3° - 6°, dΩ = 10-35 msr) onto a 2D focal-plane detector system which measured ΔE, E, position, and TOF (using the beam r.f. as a time marker).

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†University of Notre Dame, South Bend, IN.

1. R. Stern et al., Proc. Conf. on Instrum. for Heavy-ion Nucl. Res., ed. D. Schapira (ORNL Conf.-84-1005, 1984), p. 95.
2. R. Stern et al., BAPS 31, 819 (1986).
3. R. Stern et al., Rev. Sci. Instr. (in press).
4. R. Stern, Ph.D. Thesis, University of Michigan, 1987 (unpublished).

Two different detector systems were developed and tested in beam. The first was a two-dimensional gas proportional counter consisting of two perpendicular high-resistance wires, giving x, y, and two ΔE signals. This was backed by a large-area (600 mm^2) silicon stopping detector which gave E and TOF. The second system (Fig. II-41) was a solid-state SiSB telescope, with a large-area (450 mm^2), thin (28 μm) detector for ΔE and TOF backed by a special 25 mm x 25 mm, 300 μm) thick, two-dimensional position-sensitive Si E detector. The latter was developed in collaboration with he LBL detector group.[5]

The focusing properties of the solenoid spectrometer are illustrated by Figs. II-42 and II-43. Figure II-42 shows a series of images at the detector for ^{21}Ne ions of different energies from $^{110}Pd(^{18}O,^{21}Ne)^{107}Ru$ at E_{beam} = 100 MeV. When the ions are focused by the solenoid, the image is a small disk corresponding to the circle of least confusion (middle). When the ion energy is smaller or larger, the image is than a ring. Figure II-43 shows a plot of radial position, R, vs. energy at the detector for the above reaction. By taking advantage of the spectrometer's spherical aberration, i.e. the spread for R in a finite acceptance angle [$R(\theta,E)$], one can correct for kinematic shifts ($dE/d\theta$) or other angle-dependent effects.[4]

Although data analysis is only partially completed, we have some preliminary results. Separation of distinct Z groups is unambiguous, but there is some overlap of mass groups due to the limited timing resolution of 0.6 - 1 ns (~1.0 - 1.5%). A Z vs. mass identification spectrum is shown in Fig. II-44. The energy resolution, typically ~.08 - 1 MeV is worse than expected, due primarily to the spread in the linac beam which was tuned for minimum time spread. On the booster GP beam line we observed ΔE(FWHM) x Δt(FWHM) $\doteq$ 200 keV •ns for the beam. Thus $\Delta t_{beam} \doteq$ 200 ps yields $\Delta E \doteq$ 1 MeV. This limitation makes unambiguous identification of the very low cross section reaction products (e.g. ^{18}Ne, ^{14}O) difficult.

Energy spectra for $^{26}Mg(^{18}O,^{20}Ne)^{24}Ne$ and $^{110}Pd(^{18}O,^{20}Ne)^{108}Ru$ are shown in Fig. II-45. The former was obtained with a solid angle of 25 msr (θ = 3°-6°), while the latter was obtained with a solid angale of 8.5 msr (θ = 5°-6°). The spectrum for the ^{110}Pd target yields a preliminary mass excess

[5] J. Walton, Detector Group, LBL,Berkeley, CA 94720.

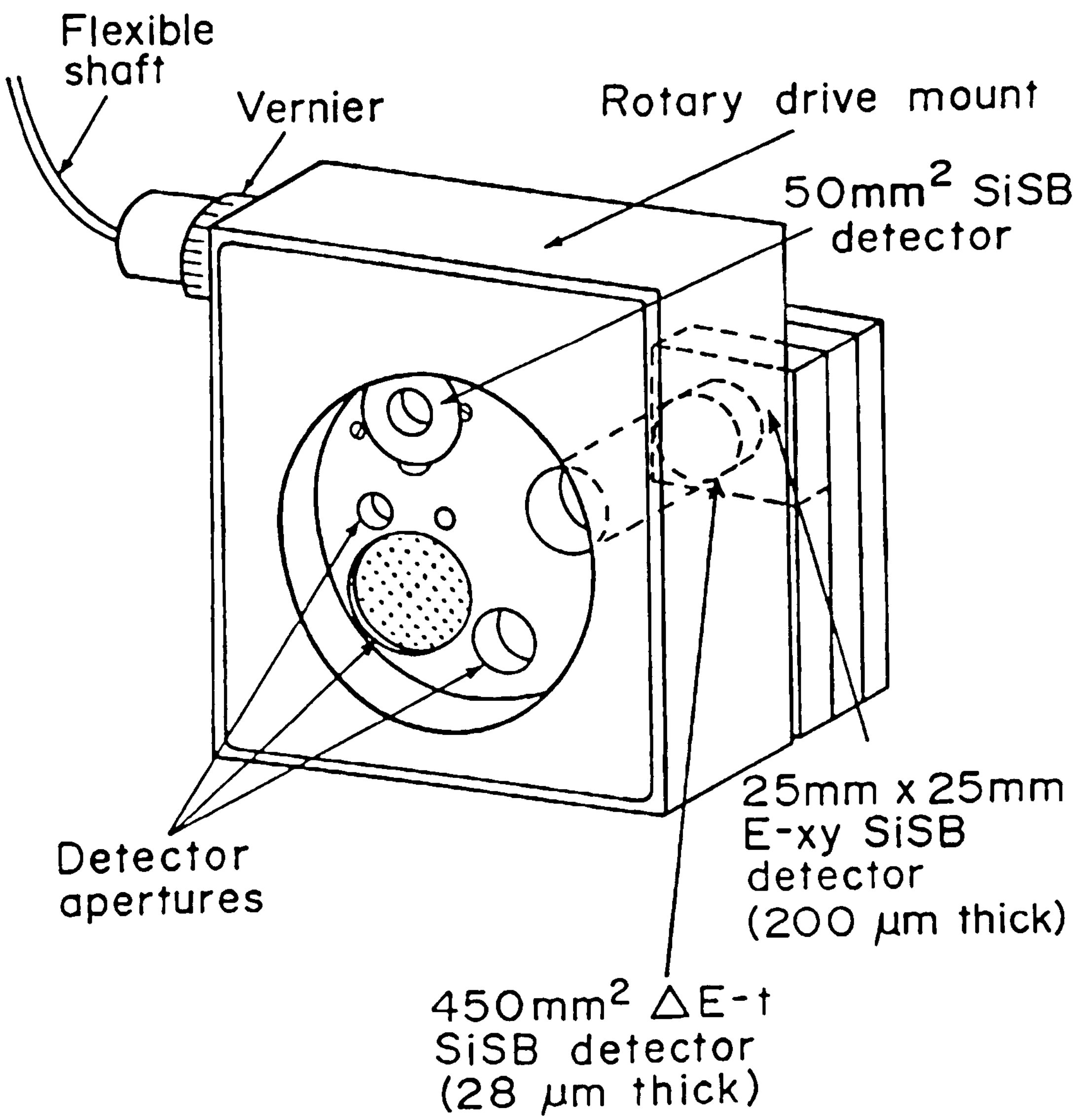

Fig. II-41. Schematic of focal-plane detector system.

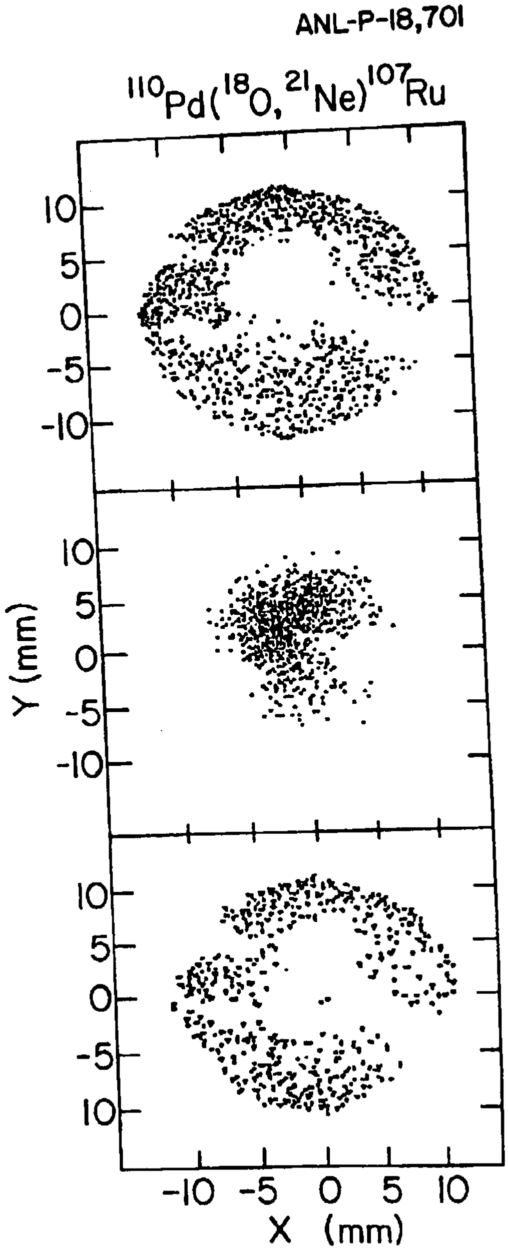

Fig. II-42. Focusing properties of the solenoid obtained using the $^{110}Pd(^{18}O,^{21}Ne)^{107}Ru$ reaction at E_{lab} = 100 MeV. The center image corresponds to the circle of least confusion obtained at focus. The upper and lower ring images are formed by ions at higher and lower energies. (See text)

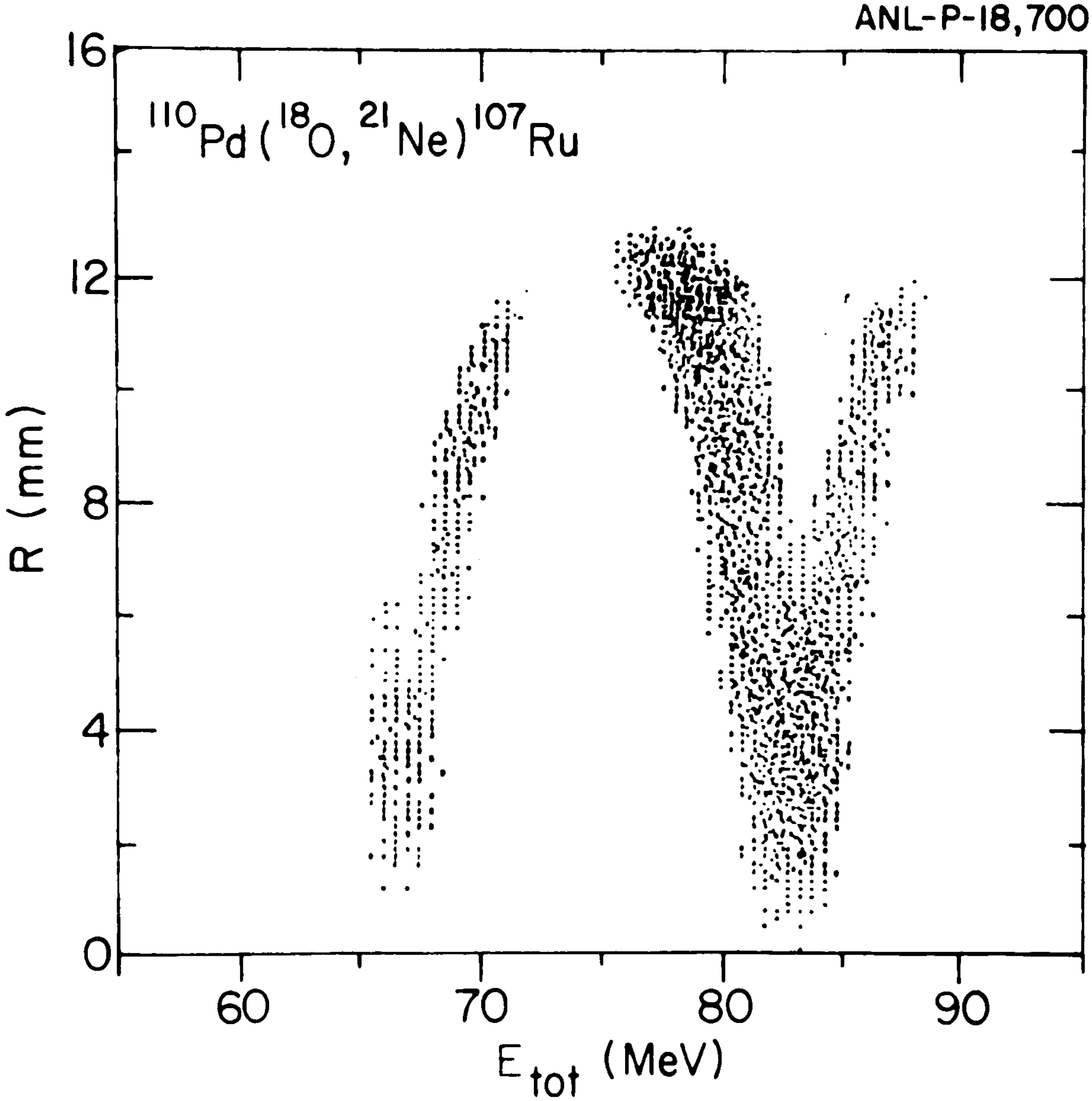

Fig. II-43. Plot of radial distance (from the circle of least confusion) R, versus energy of ^{21}Ne observed in the reaction $^{110}Pd(^{18}O,^{21}Ne)^{107}Ru$ at E_{lab} = 100 MeV.

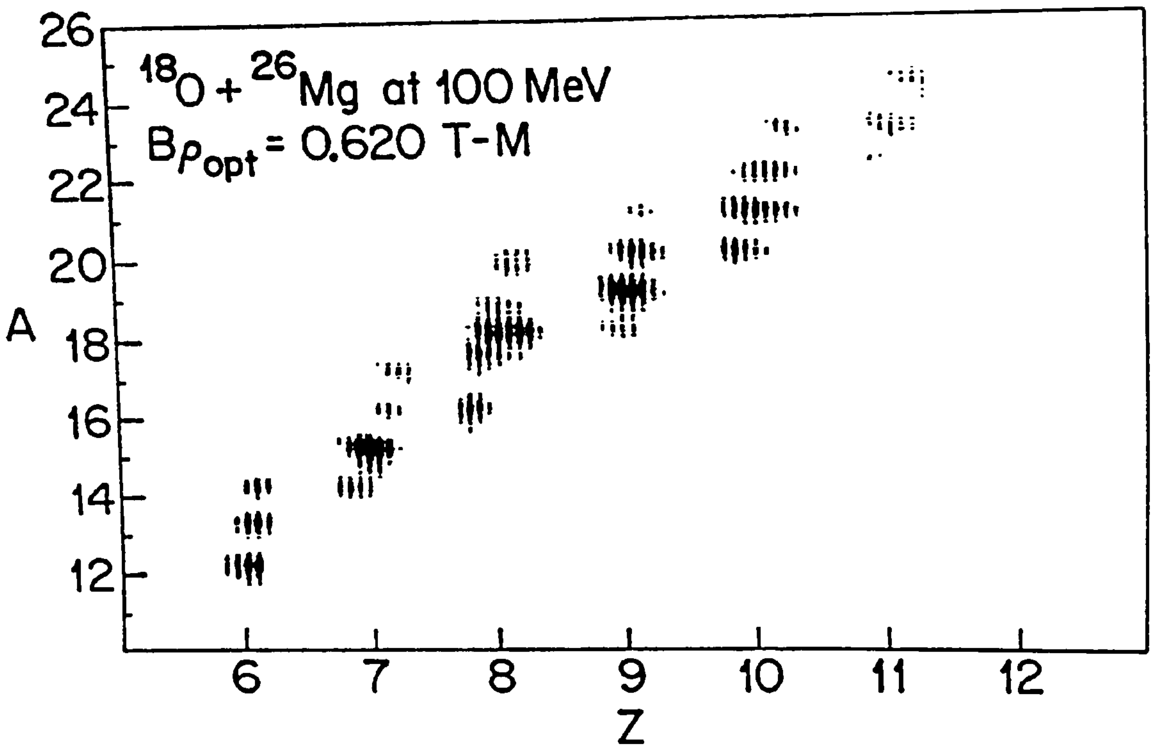

Fig. II-44. Example of a Z versus A identification spectrum obtained.

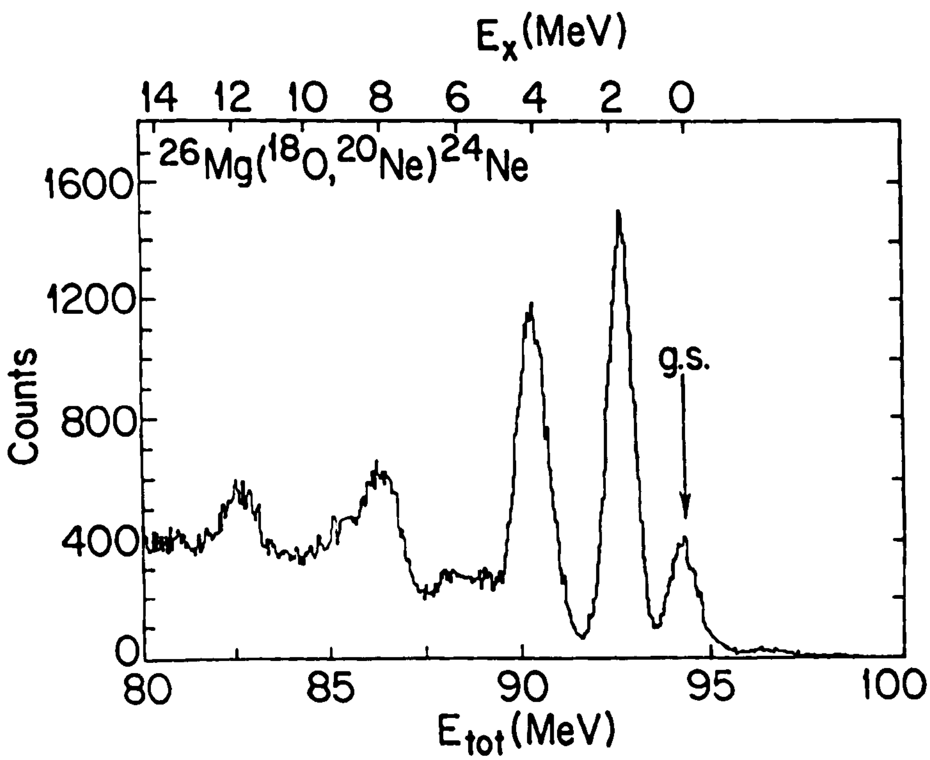

Fig. II-45. Energy spectra obtained for $^{26}Mg(^{18}O,^{20}Ne)^{24}Ne$ and $^{110}Pd(^{18}O,^{20}Ne)^{108}Ru$ reactions.

determination of -83,950 ± 115 keV for ^{108}Ru.[4] This agrees with the value of -83,700 ± 610 keV previously obtained from beta-decay.[6]

Based on the ANL-ATLAS in-beam tests, a larger solenoid magnet system has been designed. This is capable of bending ions of E/A < 40 MeV with dΩ up to 200 msr. A proposal to NSF and/or DOE is being prepared. Also, the existing magnet, which focuses ions of E/A < 5 MeV/u, has been adapted for the production of measurements using radioactive beams (^{6}He, ^{8}Li, ^{7}Be...) For this purpose, the spectrometer will be run in an asymmetric configuration (image distance ≐ 2 × object distance) to give a large solid angle (dΩ ≐ 100 msr) at the expense of a large energy bit.

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[6] A. H. Wapstra and G. Audi, Nucl. Phys. A432, 1 (1985).

o. **Detection of Evaporation Residues in the Gas-filled Split-Pole Spectrograph** (W. Henning, K. E. Rehm, M. Kaplan,* D. Moses,* W. Parker,* P. DeYoung,† J. Alexander,‡ G. Gilfoyle,‡ G. Auger,‡ and R. McGrath‡)

Coincidence experiments between evaporation residues and light particles are sometimes difficult due to the presence of the strong peak from elastic scattering at forward angles. While the separation of the evaporation residues from the beam-like particles with a magnet is generally possible, it is usually not very efficient due to the many charge states of the heavy residues. We have therefore employed the gas-filled split-pole spectrograph in order to increase the efficiency for detecting evaporation residues. Due to many charge-changing processes in the gas, the heavy residues follow a mean trajectory given by the average charge state for these particles.

The technique was successfully tested in the reaction ^{37}Cl + ^{nat}Ag. At a pressure of 1 Torr N_2 in the magnet, the total charge-state distribution of the evaporation residues had a FWHM of only 10 cm in the focal plane of the split-pole spectrograph. A coincidence experiment using this technique is planned for spring 1987.

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p. **Detection of Fission Products in Heavy-ion-induced Reactions at Forward Angles** (K. E. Rehm, J. Toke,* W. U. Schröder,* S. S. Datta,* R. T. Desonza,* I. Govil,* J. R. Huizenga,* J. L. Wile,* and W. P. Zank*)

The measurements of angular distributions of fission-like products at very small angles provide a means of studying transitional processes with properties intermediate between those of fusion-fission and of damped nuclear reactions. If the magnetic rigidity of the fission products is sufficiently different from the rigidity of the elastically-scattered particles, a magnetic spectrometer can be used in order to separate the different products. As a test for an upcoming experiment to study the tilting-mode relaxation in the reaction $^{58}Ni + ^{165}Ho$, we have studied the separation between elastic-scattered particles and fission products in the split-pole spectrograph, It was observed that only the very weak 28^+ charge state from ^{58}Ni interfaces with the fission fragments in the focal plane. Employing the 5-slit entrance aperature in the spectrograph, 5 angles can be measured simultaneously. This makes it possible to obtain high-quality angular distributions within reasonable short periods of beam time. The actual experiment is planned in late spring of 1987.

*University of Rochester, Rochester, NY.

q. **Development of a Large-area Detector for Multiparticle Coincidence Experiments** (R. R. Betts)

Several recent experiments have shown interesting nuclear-structure features in the breakup of projectiles such as ^{24}Mg, ^{28}Si, ^{32}S following inelastic scattering and transfer reactions. These experiments require the coincident measurement of energy and angles and identification of binary fragments such as ^{12}C, ^{16}O at forward angles. To date the experiments have been performed using conventional position sensitive detector telescopes which have the disadvantage of extremely-low (<1%) efficiency for detecting the events of interest. This low efficiency further complicates the extraction of quantitative information from these data as a knowledge of the efficiency, besides phase space, requires input on spins, angular correlation etc. which are not known.

To improve this we are developing a large-area detector to measure these and similar processes with high (~ 80%) efficiency and excellent energy resolution. Conceptually the device consists of two multiwire gas counters, to measure x, y and to provide time information, backed by a 5 × 5-cm silicon microstrip detector for energy and further position information. Monte Carlo similation of the breakup of ^{24}Mg following inelastic excitation such as reported by Fulton et al. indicates that this detector will be more than 100 times more efficient and still provide excellent energy resolution. The higher energies of the ATLAS beams will further improve this.

Prototype microstrip detectors have been received and will be tested for position, energy and timing response before combining with gas counters.

r. **Nuclear Target Making and Development** (G. W. Klimczak and G. E. Thomas)

The Physics Division operates a facility which produces and coordinates the production of thin targets for charged-particle-induced experiments, primarily at the ATLAS and Dynamitron accelerators. In addition, these thin films are occasionally prepared for other scientific purposes. The services of the nuclear target-making facility are available to the Physics Division and other Divisions of the Laboratory, as well as other scientific institutions. In addition to the normal requirements, research is done on new techniques, as well as on the implementation of advanced, new state-of-the-art techniques developed at other institutions.

During the past year some of the targets produced in the facility have been sandwich targets of ^{116}Cd, ^{120}Sn, ^{72}Ge, ^{82}Se, ^{64}Ni with Pb and Au backings and overlays. Other evaporated targets have included: ^{154}Sm, ^{64}Ni, ^{60}Ni, LiH, Fe, ^{57}Fe, Au, Ag, W, ^{28}Si, ^{40}Ca, MgO, ^{122}Sn, LiF, ^{6}LiF, ^{24}Mg, ^{25}Mg, ^{26}Mg, Pt, ^{192}Pt, ^{194}Pt ^{198}Pt, ^{209}Bi, ^{156}Gd, ^{166}Er, ^{165}Ho, ^{66}Zn. Rolled targets were produced of Cu, Ta, ^{90}Zr, Au, Pt, Th, Al. Other tasks included production of fine Zr powder, Zr with a diffused layer of deuterium, KBr, Formvar, Au and Ag on polyethylene and B, ^{10}B and ^{11}B self-supporting targets up to a thickness of 450 $\mu gr/cm^2$. Extremely thin carbon targets ($\sim$0.2 $\mu gr/cm^2$) were prepared utilizing Formvar and Collodion as well as very-fine electro-etched Ni support grids. Thin carbon targets of controlled resistivity were produced on quartz backings with the electron beam gun.

Procedures were developed for production of thin coatings of Teflon and Drifilm (a form of silica) on inner surfaces of small metal or glass cells to be used for polarized-ion experiments. Procedures were established for the production of multigram quantities of calcium from $CaCO_3$.

The new ultra-clean cryopump evaporator system has been completed and is routinely producing vacuum in the chamber in the mid-to-low 10^{-8}-torr range. It has been previously demonstrated that this system, backed by sorption pumps, will produce targets with significantly less hydrocarbon contamination than conventional diffusion pump systems. The argon-ion saddle-field sputter system has been installed in the cryopump system with development work on refractory metals continuing. A new small rolling mill has been obtained and is currently being utilized for the production of some targets.

The computer-controlled turbo-pumped target storage system has been completed and is currently available for the storage of highly-reactive targets.

Feasibility studies and cost evaluation are being carried out on both a large sputtering system and a new highly-focussed electron-beam-gun system. Operation of either of these systems will permit imporved efficiencies with expensive isotopes as well as enhanced capabilities for production of targets, which are not producible with present equipment. Studies are underway to determine the suitability of a small oil-free vacuum pumping system that operates from atmosphere to the 10^{-6} torr range. The unit requires no cold trapping and may be suitable for target storage and/or a small-volume (<20 liter) evaporator. Negotiations are currently underway with the manufacturer for a trial evaluation.

s. **Physics Division Computer Facilities** (L. C. Welch, D. Cyborski, T. Moog, T. Coleman, and S. Monhardt)

The VAX 780 (BITNET node ANLPHY) continues to serve as a the major facility within the Division for replay and analysis of experimental data. The additional memory, referred to in last year's report, has been installed and has helped performance greatly. A public domain program to dynamically alter priorities based on an algorithm involving CPU usage has also been implemented and has helped interactive responsiveness. However the usage of the 780 has grown from 42% of the total available in 1984 to 68% in 1986. It is clear that saturation will occur within two years and additional computing resources are needed to keep up with the requirements.

The reliability of the system has been good with one disturbing problem. In September the floating-point accelerator developed a peculiar failure,...for a very narrow range (25.21145 ± .00005) of the argument to the double-precision exponential function in FORTRAN one of two answers would randomly return, one of which was correct. The wrong answer differed from the correct one by approximately .1% and hence would be unnoticeable in most circumstances. The problem was detected by the CERN program MINUIT which checks for a time dependence in a function to be minimized. Replacement of the FPA boards cured the problem.

Disk usage has continued to increase and plans are underway to add an RA60 disk drive which has 205MB removeable packs. A single RA60 drive has the advantage that disk space can be increased by merely buying relatively inexpensive disk packs but has the disadvantage of only being able to have one pack mounted at a time.

Four dial-in modems have continued to suffice. Two of the modems have been upgraded to 2400-baud.

A DS-5 data switch (or PBX) from Equinox Systems, Inc. has been installed in the Physics Divison and has the acronym PHYLIS (for PHYsics LIne System). Presently the vast majority of offices within the Division have a PHYLIS terminal connection. Not only the 780, but also the Dynamitron and ATLAS VAXs as well as three PDPs within the Division are accessible from the PHYLIS switch. Connections to the IBMs and the MFENET are also made through PHYLIS. PHYLIS has greatly enhanced the accessibility of the computers used by the staff and much more efficiently uses resources such as computer ports, concentrators and MFE lines.

The three VAX 750s in the Division have functioned well. The DYNAMITRON VAX is routinely used for data acquisition and replay using DAPHNE. The ATLAS VAX serves as the data-acquisition system for the ATLAS accelerator and has been used by two experiments simultaneously. The 750 in the medium-energy trailer has been used at SLAC for data acquisition (but not with DAPHNE) and is also used for DAPHNE replay. All of four VAXs are connected via Ethernet using DECnet. This provides a very efficient means for software and system maintenance.

Bids for a MicroVax II system have been received for the medium-energy group to analyze the data from the neutrino oscillations experiment and are currently being evaluated. It is anticipated that a second MicroVax II will be ordered for area II data room to replace the PDP 11/45, which is the only remaining accelerator-based 11/45 data-acquisition system.

t. **The Data-acquisition System DAPHNE** (L. C. Welch, T. Moog, Y. Y. Zhou, T. Coleman, S. Monhardt, and R. Daly*)

DAPHNE, the data-acquisition system developed for ATLAS, is routinely used to this point and has been exported to three user laboratories as a replay system. Major enhancements implemented during the past year are multiple-event types, variable-length events, pseudo-events, linearizations, and simultaneous use by two experiments. Planned for the future are PAUSE/RESUME, selective taping during replay and better diagnostics in tape handling. Graphics speed and reliability have been significantly upgraded.

The only major work seen that is necessary to support a MicroVax II is to develop the Q-Bus-to-Multibus interface. Several Q-Bus-to-UNIBUS converters have been examined and one has been found that works with the present UNIBUS-to-Multibus adapter.

*Electronics Division, ANL.

u. **SCAMP - A General-purpose Process-control System for the Experimental Facilities at ATLAS** (S. J. Sanders)

SCAMP has been developed as a general-purpose, user-friendly tool allowing experiments to modify conditions at the ATLAS experimental stations by way of commands issued at a computer terminal in the control room. The system is also capable of minitoring pressures and voltages and alerting the experimenter if the value of a monitored quantity goes outside of its predefined range. Considerable flexibility is maintained by implementing all process control functions through CAMAC modules. SCAMP was made fully operational during the early part of last year, and was used subsequently in several experiments at the 36" scattering chamber. Here its primary use was to control the ring, upper chamber, and target motions for the chamber and to check rotation requests for the possible collision of detectors. A problem encountered in these initial runs using SCAMP and manifested by periodic computer crashes has been corrected with the upgrade of the computer processor (now using a PDP 11/73 processor) and by obtaining a new serial i/o port for communication with the CAMAC crates. Work has begun in implementing control functions for the Enge split-pole spectrometer in SCAMP, and various other system upgrades are being considered.

III. THEORETICAL NUCLEAR PHYSICS

The principal areas of research in the nuclear theory program are:

A. Nuclear forces and sub-nucleon degrees of freedom.
B. Intermediate energy physics with pions, electrons and nucleons.
C. Heavy-ion interactions.
D. Variational calculations of finite many-body systems.
E. Nuclear structure studies in deformed and transitional nuclides.
F. Binding of hypernuclei from ΛN and ΛNN forces.
G. Quantum mechanics with magnetic charges or flux lines.

A. NUCLEAR FORCES AND SUBNUCLEON DEGREES OF FREEDOM
(F. Coester, R. B. Wiringa, V. R. Pandharipande* and Others)

Much of our work is motivated by three central questions. (1) What should be the active degrees of freedom in a microscopic description of nuclei? (2) What is the Hamiltonian that governs the nuclear many-body dynamics? (3) What can electromagnetic probes reveal about short-distance nuclear structure?

For conventional nuclear theory, which assumes that nucleons are the only active degrees of freedom, it is not required that two-body forces alone are sufficient, but it is essential that the same Hamiltonian account for both light and heavy nuclei and that the importance of the n-body forces decrease rapidly with increasing n. We have previously established that two-body forces alone cannot account for the properties of nuclear matter. For three-body forces as well as two-body forces, the long-range part is governed by the pion exchange mechanism while acceptable short-range features must first be determined phenomenologically. We have constructed a reasonably good three-body force, but further improvements are needed. High accuracy in the calculation of the ground-state properties is absolutely essential and we continue to make necessary improvements in this area.

In 1986 our calculations of neutron matter using the above potentials revealed evidence for a pion condensate at a density about 1.6 of the nuclear matter saturation density. We will be improving these calculations during the current year. We have computed longitudinal structure functions and nucleon momentum distributions for ^3H, ^3He, ^4He and nuclear matter.

Evidence for subnucleon degrees of freedom from spectroscopic and elastic scattering data is always indirect. In contrast, inclusive deep-inelastic scattering reveals directly the charge- and momentum-carrying constituents. Deep inelastic electron scattering provided the definitive evidence for the existence of quarks and gluons. Recent data on nuclear effects in deep-inelastic lepton scattering are thus of prime importance. We have shown that the dynamics of nucleons and pions with unaltered quark structure can account for the existing data within the experimental uncertainties. We are turning our attention to semi-inclusive processes; these will require improvements in the calculations of the excess pion densities in nuclei.

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*University of Illinois, Urbana, IL

There is little doubt that a full understanding of the nuclear force must be based on the underlying quark dynamics. In practical terms this involves the study of constituent quark models, which should be based on the essential physical features of quantum chromodynamics and be subject to the requirements of relativistic invariance. We are engaged in the study of such models.

Much of the quantitative information that will determine the success or failure of competing models will come from electromagnetic probes. Observed quantities are directly related to matrix elements of the electric charge and current densities. A valid interpretation requires mutually-consistent representations of the current operators and the target wave functions. Work in progress on the form factors of the deuteron should provide a continuous transition between the regime of low-momentum transfer and the asymptotic regime governed by perturbative QCD.

a. **Nuclear Effects in Deep-Inelastic Lepton Scattering**
(F. Coester and E. L. Berger*)

Deep-inelastic lepton scattering by nuclei is a means to observe quark and antiquark distributions per nucleon in nuclei. These distributions are found to depend on the nucleon number A. The ratio of the structure functions $F_2^{Fe}(x)/F_2^{D}(x)$ is increased above unity by about 5% for $x < .2$ and decreased for $.2 < x < .7$. Earlier uncertainty concerning the amount of small-x enhancement was removed by new data which became available in 1986. The physical assumptions, made to account for the observed nuclear effects, fall into three distinct categories: (1) The assumption of "color conductivity"; it is assumed that quarks migrate between nucleons in the nucleus like the electrons in a semiconductor. (2) The assumption of an independent-particle, or "mean-field" model of nuclear structure. In this approach the structure functions per nucleon of a nucleus are interpreted as structure functions of individual nucleons with properties modified by the medium. (3) Conventional nuclear many-body dynamics, this implies the presence in the nucleus of constituent hadrons other than the nucleons, i.e. mesons and isobars. These nonnucleonic constituents contribute to the structure functions of the nucleus, both directly through their own quark structures and indirectly through the momentum balance of all constituents. We have concentrated in the past on the successful development of this last approach. We are now preparing a review article on this work.

A successful account of inclusive deep-inelastic scattering data required only rough calculations of the relevant momentum densities of pions in the nucleus. We are now addressing questions raised by observations of semi-inclusive pion production. Substantial theoretical uncertainties in the calculation of pion densities need to be removed to predict the outcome of more precise experiments.

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b. **Excess Densities of Pions in Nuclei** (F. Coester)

Any phenomenological meson-nucleon vertex interaction implies a self-energy, which is associated with the nucleon's meson cloud, of the isolated nucleon. The modification of this meson cloud by neighboring nucleons gives rise to nuclear binding and an enhancement (or depletion) of the meson cloud. For any momentum the mesons are enhanced if the interaction, for a momentum transfer equal to the meson momentum, is attractive and depleted if it is repulsive. The momentum distribution of the mesons is proportional to the Fourier transform of the two-nucleon density and the matrix elements of a two-body operator that depends quadratically on the form factor of the meson-nucleon vertex. While excess pion numbers in nuclei depend only on the long-range parts of the pion-exchange potential and of the two-nucleon density, the pion momentum densities depend, in an essential manner, on the assumed short-range features of the $NN\pi$ vertex and on the short-range features of the two-nucleon densities. The sensitivity to such model dependencies was not crucial for the interpretation of the EMC effect, but for the interpretation of future experiments it will be important to establish more precisely the quantitative effects of model assumptions and approximations.

c. **Phase Transitions in Neutron Matter**
(R. B. Wiringa, A. Fabrocini* and V. Fiks†)

Theoretical calculations are being made for the equation of state of dense neutron matter. These calculations are based on realistic Hamiltonians, including two-body potentials v_{ij} fit to NN scattering data and a three-body potential V_{ijk} fit to the binding energies of ^{3}H and ^{4}He and to the saturation density ρ_0 of nuclear matter. Variational wave functions and hypernetted-chain (HNC) integral equations are used to compute the equation of state. This theoretical framework is significantly different from traditional work on pion condensation, which concentrates on the one-pion-exchange (OPE) interaction, lumps all effects of correlations between nucleons into the parameter g', and uses RPA to calculate many-body effects.

Preliminary results indicate the possibility of a phase transition akin to pion condensation in neutron matter at $\approx 1.6\ \rho_0$ for the Hamiltonian consisting of the Argonne v_{14} + Urbana model VII interactions. This transition is critically dependent on the presence of the two-pion-exchange (TPE) V_{ijk}, which effectively provides coupling to Δ degrees of freedom

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suppressed in v_{ij}. It is also sensitive to the v_{ij} used, since no transition is observed if the Urbana v_{14} interaction is substituted. The pionic nature of the transition is indicated by a large change in the expectation values of the π-exchange v_{ij} and 2π-exchange V_{ijk}. At higher densities, the repulsive component of V_{ijk} dominates, and the equation of state is quite stiff. This equation of state leads to neutron stars with a maximum mass of $\approx 2\ M_{\odot}$. The phase transition could produce some interesting structure and may indicate a role for π-cooling mechanisms in the early history of neutron stars.

Our current efforts are focused on improving the energy expectation value calculation. This is being done in conjunction with the improvements in the matter code required by our studies of structure functions in nuclear matter (Sect. A.d). We have also generalized the search procedure for finding optimal parameters of the variational trial function. We wish to ensure that any observed phase transition is not an artifact of the calculational procedure.

d. <u>Structure Functions in Nuclear Matter</u> (R. B. Wiringa, V. R. Pandharipande* and S. Fantoni†)

We have calculated the static structure function $S(k)$ and static longitudinal structure function $S_L(k)$ in nuclear matter as part of a general study of structure functions in many-body systems (see also Sects. A.e and D.a). $S_L(k)$ is also known as the Coulomb sum rule in finite nuclei and has been measured in ^3He, ^{12}C, ^{40}Ca and ^{56}Fe by integration over the quasielastic peak of inelastic electron scattering. In infinite systems $S(k)$ is simply related to the two-body distribution function $g(r)$. In nuclear matter $g(r)$ has a central part g_c plus spin and isospin components, g_σ, g_τ, etc. $S_L(k)$ is a function of both g_c and g_τ. In the limit $k = 0$, both $S(k)$ and $S_L(k)$ must vanish.

Our calculations in nuclear matter are based on variational wave functions with expectation values evaluated in a diagrammatic cluster expansion. We found that with our existing code g_τ did not behave properly and $S_L(k = 0)$ did not vanish. The evaluation of additional diagrams was

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required to obtain the correct behavior, and a very general set of higher-order terms was added to the code. Fortunately the net effect of these diagrams on the ground-state energy is small. We also noted that a similar restriction on the long-wavelength behavior of g_σ does not apply when tensor forces are present, a feature which may not be generally known.

The calculations are compared with data in Fig. III-1. We find that the data for heavy nuclei do not agree with the nuclear-matter calculations, and in fact are inconsistent with the required positivity of the two-proton distribution function. The likely explanation is that in heavy nuclei the longitudinal strength is spread out and some may be lost because it is beyond the quasifree peak. The general work on static structure functions has been submitted for publication.

e. **Variational Monte Carlo Calculations of Few-Body Nuclei**
(R. B. Wiringa, R. Schiavilla* and V. R. Pandharipande*)

We have continued our program of studies on the three- and four-body nuclei using the variational Monte Carlo method. In the past year we have confirmed our earlier calculations of the nucleon momentum distributions using a different sampling algorithm that is closer to that used in the studies of atomic helium drops. We have also calculated the static structure function S(k) and longitudinal static structure function $S_L(k)$ for ^{3}H, ^{3}He and ^{4}He. Our $S_L(k)$ for ^{3}He is in very good agreement with the experimental results obtained at Saclay, although the errors in the data are too large to derive detailed information about nucleon correlations.

These calculations have been carried out both with our own variational wave functions and with the superior 34-channel Faddeev wave functions of the Los Alamos-Iowa group. Our studies with the Faddeev wave function also confirm their results for the binding energy and density distribution of the trinucleon system. This work was presented at an international conference in Rome and appeared in its proceedings.[1]

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[1]R. B. Wiringa et al., Few-Body Systems, Suppl. 1, 130 (1986).

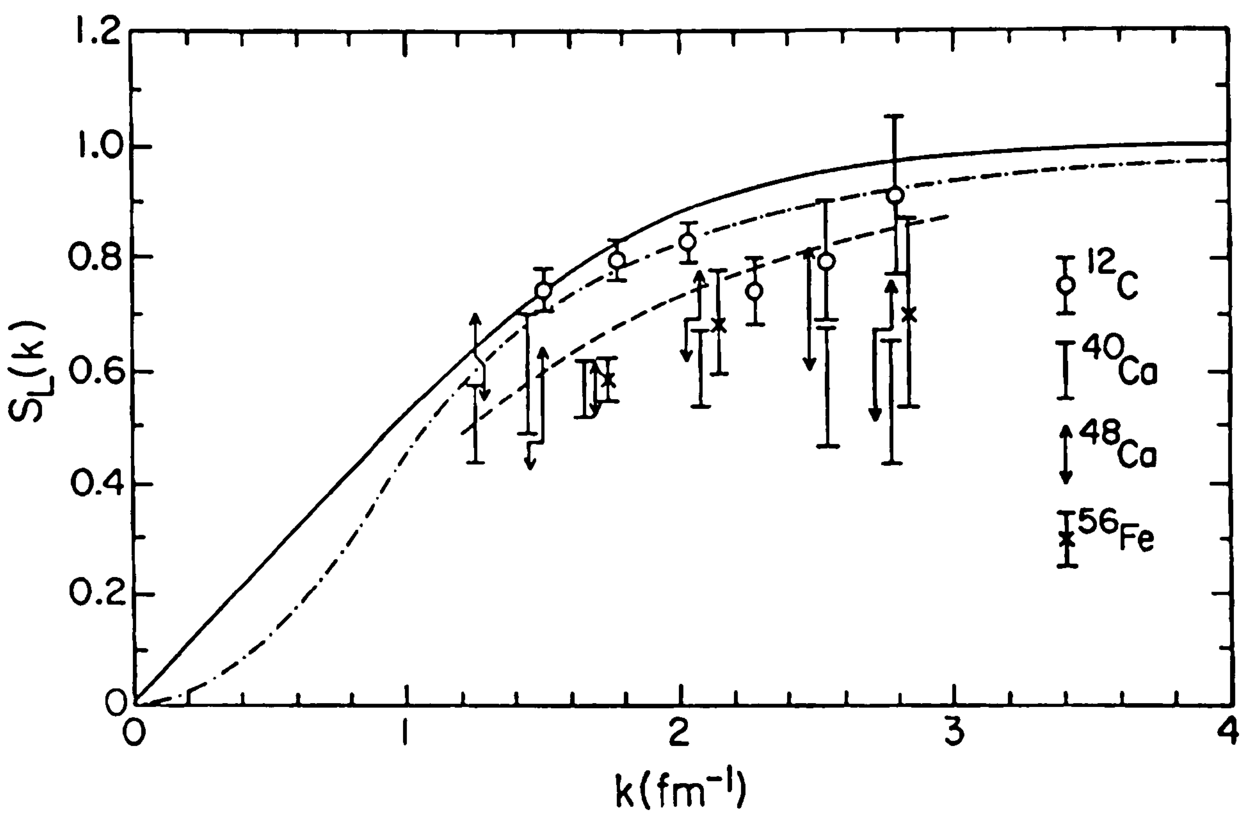

Fig. III-1. The $S_L(k)$ for nuclear matter is shown by the full line, while the dashed line is an estimate of the reduced $S_L(k)$ expected from the quasifree peak. The data are from Saclay. The dash-dot curve is an extrapolation of the ^{12}C data whose Fourier transform gives a two-proton distribution function that is not positive definite.

f. **Electromagnetic Form Factors of the Deuteron**
(F. Coester, P.-L. Chung,* B. D. Keister† and W. N. Polyzou*)

Measurements of the deuteron form factors over a wide range of momentum transfer can provide important clues to the role of subnucleon degrees of freedom in nuclear dynamics. For a meaningful calculation of the form factors it is essential that the current-density operators and the deuteron wave function transform under Lorentz transformations in a mutually consistent manner. Conventional "nonrelativistic" deuteron wave functions can be interpreted as relativistic wave functions of a deuteron at rest. The general Lorentz transformations of the full wave function depend on the choice of a subgroup of kinematic transformations which is independent of the interactions. In the light-front form the dynamic transformations are the rotations about axes perpendicular to a longitudinal direction. The advantage of the light-front form stems from the following features: (1) The initial and final states of the deuteron are related to each other and to the deuteron's rest frame by kinematic transformations. (2) The plus component of the four-vector current density is invariant under all kinematic Lorentz transformations. Matrix elements of this component alone are sufficient to determine all deuteron form factors. (3) All matrix elements of the single-nucleon current required for the calculation of deuteron form factors are related to each other by kinematic Lorentz transformations. These features allow a clean separation of the effects of one- and two-body currents for arbitrary momentum transfers without nonrelativistic approximations. We have calculated deuteron form factors with wave functions obtained from the Reid-Soft-Core, Paris, Argonne V14 and Bonn potentials. Different published parameterizations of the nucleon form factors represent the experimental uncertainties in these form factors. The *ad hoc* addition of minimal two-body currents designed to assure invariance under the dynamical rotations does not affect the results significantly. At sufficiently high momentum transfer we must expect a breakdown of the two-nucleon picture of the deuteron. We find no evidence that this happens for momentum transfers, $Q^2 < 8$ GeV^2. A paper on this work is being prepared for publication.

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g. **Quark Models of Hadron Interactions** (F. Coester and W. N. Polyzou*)

Quark models of single hadrons have been successful in accounting for hadron spectroscopy. They are not automatically applicable to multi-hadron dynamics. We are investigating quark models of multi-hadron dynamics which emphasize the following features: (1) spatial confinement of quarks tied to color confinement (gauge invariance), (2) absence of long-range Van der Waals forces, (3) Poincaré invariance. Starting from ideas due to Greenberg and Hietarinta we realize these requirements in zeroth order by models which feature quarks confined to noninteracting hadrons, each of which has infinitely-many stable excited states. The manifest defects of these zero-order models are removed by the interactions: (1) String-breaking interactions remove the stability of the unphysical excited states in a manner that guarantees the existence of scattering states with the right asymptotic properties. (2) String-rearranging interactions establish the short-distance exchange symmetry between quarks in different hadrons. We developed a pilot model of a quark-antiquark system coupled to two-quark-two-antiquark states with a string-breaking interaction. This model, based on the "instant form" of relativistic dynamics, exhibited unrealistic spectral properties and was unsuitable for the study of electromagnetic properties of hadrons. We plan to investigate better models, using "front-form" dynamics, with emphasis on electromagentic properties.

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B. INTERMEDIATE ENERGY PHYSICS

(C.-R. Chen, H. Esbensen, T.-S. H. Lee, H. J. Lipkin* and Others)

Our study of intermediate energy physics consists of three parts. The first part is the development of a theory which can describe the excitations of non-nucleonic degrees of freedom in intermediate energy nuclear reactions. The major task in this part of the work is to determine the parameters of the considered model Hamiltonian by carrying out extensive calculations of πN, NN and πd reactions. In 1986 we have completed the development of such a model, taking into account the pion and Δ degrees of freedom. We are now moving into the direction of systematically including the quark dynamics in the short-range part of the model. This involves a hyperspherical-coordinate three-body calculation of hadron form factors, a cloudy-bag model study of πN scattering and the development of a quark compound model of the πNN interaction.

The second part of our research is the use of the constructed model to study nuclear reactions induced by intermediate energy probes. Our current focus is on the study of electromagnetic production of Δ's or pions from light nuclei. We proceed by first constructing a model of current operators for the coupled $\pi N+\Delta$ system. The model is then used in the study of $(e,e'\pi)$ and (γ,π) reactions on deuteron and ^{3}He. We are also continuing our effort in developing a microscopic description of Δ-nucleus interactions and pion absorption.

The third part is a study of the response of heavy nuclei to intermediate-energy hadronic probes. We have reviewed the theoretical description of the Gamow-Teller resonance observed in charge-exchange reactions. We have discussed the empirical nucleon-nucleon interactions in detail, both between free nucleons and the effective interactions in a nuclear medium. We have also applied the previously-developed surface-response model to the spin response of nuclei, induced by the scattering of polarized protons.

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a. **Unitary Theory of Mesonic and Dibaryonic Excitations in the πNN System** (T.-S. H. Lee and A. Matsuyama*)

In 1986 we continued our efforts in developing the πNN theory we proposed in 1985. Our objective is to obtain a unified description of all NN and πd reactions. The mesonic mechanism is built into the theory by extending the conventional meson theory of nuclear forces to include the isobar Δ excitation. The dibaryonic excitation at short distance is introduced according to current understanding of six-quark dynamics. The theory is free of the nucleon mass renormalization problem and is therefore tractable in practice. The model Hamiltonian consists of: (a) V_{BB} for two-baryon interactions between NN, NΔ and $\Delta\Delta$ states, (b) $h_{\pi N \leftrightarrow \Delta}$ for Δ excitation, (c) $v_{\pi N}$ for πN two-body interactions in nonresonant channels, (d) $F_{\pi NN \leftrightarrow NN}$ for nonresonant pion production, and (e) $H_{D \leftrightarrow BB}$ for the formation of a dibaryon state D. The projection technique is applied to express all NN and πd reaction transition matrix elements in terms of solutions of a two-body Lippman-Schwinger equation defined in $NN \oplus N\Delta$ subspace and a Faddeev-Alt-Grassberger-Sandhas equation defined in $N\Delta \oplus \pi NN$ subspace. Practical numerical methods have been developed to solve these two equations without making a separable expansion of the baryon-baryon interaction. This makes possible calculations based on the most sophisticated meson theory of the nuclear force.

In 1986 we completed our study of the limitations of the conventional meson-exchange parameterization of πNN model. This was accomplished by examining in detail the extent to which the NN and πd data can both be described by a class of meson-exchange πNN models. The considered models are constructed by using a previously-developed subtraction procedure to extend the Paris, Bonn, Argonne V14 and Reid potentials to include the coupling to the pion production channel. The only freedoms of the constructed πNN model Hamiltonian are in the choice of the starting low-energy NN potential and the cutoff parameters of the form factors of the $V_{NN \leftrightarrow N\Delta}$ and $F_{NN \leftrightarrow \pi NN}$ transition interactions. Our main conclusions are: (a) The main features of the NN phase shifts and various NN total cross sections up to 1 GeV are reproduced. The model can, therefore, be used as a reasonable starting point in our current study of intermediate-energy nuclear reactions. (b) The main difficulty of the meson-exchange model is in reproducing the strong energy dependence of polarization total cross sections

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$\Delta\sigma_T^{tot}$ and $\Delta\sigma_L^{tot}$ near 800 MeV. This indicates that either our construction method based on the subtraction is too limited to account for "the correct" meson-exchange mechanisms, or some genuine quark dynamics, which is beyond the conventional phenomenological parameterizations of baryon-baryon interaction at short distances, have already been revealed in the intermediate-energy πNN data. (c) Agreement of the calculated πd cross sections with the data is comparable to the NN case, and is similar to the existing πd calculations. A paper describing this study has been submitted for publication.

b. **Unitary Meson-Exchange Calculation of NN→NNπ Reaction**
(T.-S. H. Lee and A. Matsuyama*)

Within our unitary πNN theory a set of coupled-integral equations has been developed for the study of pion production from NN collisions, and has been applied to calculate the coincidence cross sections of $pp\rightarrow pn\pi^+$ at 800 MeV. The calculation involves solving a Faddeev-Alt-Grassberger-Sandhas scattering equation for the final πNN state and a NN$\oplus$NΔ coupled-channel equation for the initial NN state. We have developed a procedure using the spline-function method to solve the Faddeev-Alt-Grassberger-Sandhas equation directly on the real momentum axis. The importance of using a unitary approach to treat the initial NN and final πNN scattering is analyzed in detail, in order to understand the results obtained in several previous approaches by Betz, Dubach et al., and Verwest. The calculated cross sections reproduce the main features of the data both in magnitude and shape. The main difficulty of the present theory is found to be in reproducing the polarization data A_y. Our results provide further evidence that the πNN dynamics cannot be described completely by the conventional meson-exchange model. A paper describing these results has been published.

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c. **Study of Quark Compound Model of Nucleon-Nucleon Interactions**
(T.-S. H. Lee and C. Fasano*)

Our extensive unitary πNN studies have indicated that the conventional parameterizations of NN interactions at short distances in terms of meson-baryon-baryon form factors or a local repulsive core could be

*Thesis Student, University of Chicago, C inadequate in the intermediate-energy region. We are investigating the possibility of expressing the short-range baryon-baryon interaction in terms of excitations of six-quark systems. Following our πNN formulation and the QCB approach proposed by Simonov, it is assumed that the hadronization of six-quark states can be effectively parameterized as a vertex interaction HD→BB localized at a given distance. In 1986 we constructed such a model to describe NN s-wave scattering up to 1 GeV. We found that the s-wave phase shifts can be accurately described by the excitations of two six-quark states with masses of 2130 and 3300 MeV. The lower one can be related to the MIT Bag-model prediction through the P-matrix interpretation of Jaffe and Low. We then show that the effect of the extracted higher six-quark state can be replaced by the much-better-understood intermediate-range meson-exchange force implied by the Chiral invariance. We have also investigated the implications of the model in the study of electron scattering from deuteron. A paper describing this work is being prepared.

d. **Electromagnetic Production of Pions from Light Nuclei** (C.-R. Chen and T.-S. H. Lee)

An important application of our πNN model is the study of electromagnetic excitation of Δ and its associated pion production from nuclei. To carry out such a study, we are constructing current operators for a coupled $\pi N + \Delta$ system. Starting with a Chiral invariant cloudy-bag model Lagrangian, the electromagnetic interaction is introduced by minimum coupling. We then deduce the form of the current operator from the perturbation expansion of the S-matrix of N(e,e'π). To make the current operator square-integrable, each interaction vertex is regularized with appropriate form factors. We are determining these form factors by fitting the available data of p(e,e'π) and p(γ,π). Our objective is to use the constructed model to study (e,e'π) from deuteron and ^{3}He. In a calculation including only the impulse pion current, we have shown that the pion rescattering from the second nucleon has about a few-percent effect in determining the longitudinal cross section of the d(e,e'π) reaction. The result has been used in setting up an experiment soon to be performed at Saclay. This calculation is being extended to account for all current operators being determined in our p(e,e'π) study and final πNN scattering amplitude generated from our unitary meson-exchange πNN model described in Sec. B.a.

e. **Photo and Electroproduction of Δ as a Test of Deltas in Nuclei**
(T.-S. H. Lee and Harry J. Lipkin*)

With very general assumptions of photonuclear dynamics, various relative probabilities of producing Δ's or π's from ^{3}He are calculated from symmetry properties. We have found a large enhancement factor for detecting a Δ component in measuring the π^+/π^- ratio in the ^{3}He (e,e'π) coincidence measurement. Our results suggest that coincidence measurements detecting charged pions in photo and electroproduction of Δ's from ^{3}He can be a clear test of the presence of Δ's in nuclei. The most direct test is to see whether a Δ^{++} distribution with respect to the invariant mass of the π^+p subsystem can be mapped out in the triple-coincidence (e,e'πN) measurement since no Δ^{++} can be produced in the conventional Δ photoproduction from nucleons. The separation of the longitudinal and transverse components is also a way of identifying the Δ component in nuclei. A paper describing this result has been published.

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f. **Quark Potential Model Study of Baryon Structure**
(T.-S. H. Lee and C.-D. Lin*)

The nonrelativisitic quark potential model has been very successful in describing the spectra and some static properties of low-lying baryons and mesons. It is therefore interesting to explore the prediction of the model in the higher mass region where the rotational and vibrational excitations of the quark configurations dominate. In addition, it is important to further establish the validity of the model by examining its predictions for other dynamical quantities, such as the electromagnetic form factors. To carry out such a study it is necessary to go beyond the existing perturbative approach and solve the genuine three-body problem involving a confining potential. We have made progress in this direction in 1986 by developing an efficient numerical method for the solution of the three-body Schrödinger equation in hyperspherical coordinates. The solutions are expanded in terms of dynamical hyperspherical functions calculated nonperturbatively from the confining potential and the diagonal part of the quark-quark hyperfine interaction. The effect of the off-diagonal hyperfine interaction is then calculated by

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diagonalization in the space constructed from these dynamical hyperspherical basis states. In an exact-soluable Harmonic-oscillator model, the method proves to be accurate within a few percent in reproducing both the spectra and wave functions. The method is being applied to construct models for describing S (strangeness) = 0 baryons. Our main focus is to examine the validity of the usual perturbative approach and to explore the electromagnetic form factors of nucleon, delta and Roper resonance. We are also studying the properties of charmed baryons which are being searched for in several laboratories.

g. **Application of Unitary πNN Model in the Study of Intermediate Energy Nuclear Reactions** (T.-S. H. Lee)

A microscopic understanding of Δ propagation and pion absorption in nuclei is the basis of a unified description of intermediate-energy nuclear reactions. By employing the separable πNN model of Betz and Lee, we have made progress in this direction in the past few years by carrying out: (a) Bruckner-Hartree-Fock calculations of Δ-nucleus potential, and (b) microscopic calculations of two-nucleon absorption of pions by nuclei. With the development of our πNN model described in B.a, we are reinvestigating these two problems from the point of view of meson-exchange. In addition, we will apply our microscopic approach to study electromagnetic production of Δ in nuclei. A review-type article describing this work will be prepared for publication.

h. **Effects of ππ Correlations in πN Scattering** (John A. Johnstone and T.-S. Harry Lee)

The primary intent of this work is to gauge the significance of ππ correlations in πN interactions. The P_{11} πN channel is particularly appropriate for studying second-order effects since the low-energy phase shifts result from delicate cancellation of repulsive and attractive mechanisms. The standard cloudy-bag-model description of πN scattering is extended to include contributions at the two-pion level. The fundamental ππ interactions are constructed in a phenomenological separable form consistent with the known ππ s- and p-wave phase shifts. This interaction is then embedded in the πN problem to account for scattering of the incident pion from the nucleon's virtual pion cloud. A self-consistent analysis of the coupled πN, $\pi\Delta$, and πN^* (1470) systems results in excellent reproduction of both the phase shifts and inelasticity in the πN P33 channel up to 2 GeV. In the P11 channel, without two-pion intermediate states, no acceptable fit to the data is possible for any values of the bag parameters. The additional attraction provided by the incident π scattering from the virtual pion cloud is essential for reproducing the low-energy phase shifts and fixing their sign change at the correct energy. A paper describing this work has been published.

i. **The Strange Quark Mass in a Chiral SU(3) Bag Model**
(John A. Johnstone)

The cloudy-bag model of baryon structure is extended to include the coupling of quarks to kaons, according to $SU(3)_L \otimes SU(3)_R$ symmetry. Assuming that a single set of bag parameters apply to both the octet and decuplet, the self-energy corrections of the baryons are calculated to the order of two-pion and one-kaon intermediate states. An excellent reproduction of the mass splittings between isomultiplets is obtained and it is concluded that these splittings are entirely due to mesonic effects. The strange quark mass in this treatment is degenerate with the up and down quarks, and consistent with zero. This is radically different from conventional approaches which assign the strange quark a mass some 200 MeV or more greater than that of the up and down. This work has been published.

j. **S- and P-Wave η Production in an SU(3) Bag Model**
(John A. Johnstone)

The $\pi N \to \eta N$ reaction mechanism is analyzed using the chiral SU(3) version of the cloudy-bag model. $(56,1^-)$ and $(70,1^-)$ quark structures are identified with the N(1535) and N(1650) S_{11} resonances, and $(56,0^+)$ with the P_{11} N(1440). A simultaneous fit to the πN elastic phase shifts and ηN production cross section determines the η-η' mixing angle to be $\sim -25°$. The model is being applied to study η-production from nuclei. A paper describing this result has been submitted for publication.

k. **Nuclear Structure in the (p,π^+) Reaction** (D. Kurath)

The relative cross sections for exciting particular states in the (p,π^+) reaction near threshold have been calculated assuming dominance of the elementary $pp \rightarrow d\pi^+$ channel. The following assumptions were made: (1) The $pp \rightarrow d\pi^+$ channel was embedded in the nucleus restricting the deuteron to be in a ^3S state. (2) Targets were assumed to have $(0s)^4(1p)^{A-4}$ configurations and final states either $(0s)^4(1p)^{A-3}$ or $(0s)^4(1p)^{A-4}(2sd)^1$ depending on parity. Harmonic oscillator functions were assumed in order to facilitate cluster expansions. (3) The embedded reaction was treated in lowest order in ξ, where ξ is the relative separation of the incident and struck protons. (4) Plane waves were used for the incident proton and outgoing π^+.

Results were obtained by using shell-model information as input in calculating t-matrix elements for ^{12}C and ^{13}C targets (see Fig. III-2). Speakeasy programs were written that can treat the large amount of angular momentum coupling needed in these calculations. The results were compared with data obtained with incident protons of 200 MeV at the Indiana cyclotron. The strong states can be accounted for by the calculation, and an approximation was obtained which includes the most important part of the nuclear structure information.

ℓ. **The (p,n) Reaction and the Nucleon-Nucleon Force**
(H. Esbensen and G. F. Bertsch*)

We have completed the review article on "The (p,n) Reaction and the Nucleon-Nucleon Force". The (p,n) charge-exchange reaction is a powerful tool to study the isovector spin response of nuclei at intermediate energies. Its spectroscopic characteristics are closely related to the interaction between free nucleons, and we discuss the empirical properties of the free t-matrix interaction in detail.

The conventional method used to extract the Gamow-Teller strength in nuclei from measured (p,n) cross sections is discussed. Given the interaction between the projectile and nucleons in the target nucleus, the cross sections for inelastic excitations can be calculated in the Distorted Wave Impulse Approximation. The zero degree cross section for individual Gamow-Teller transitions is proportional to the strength of the transitions. The normal

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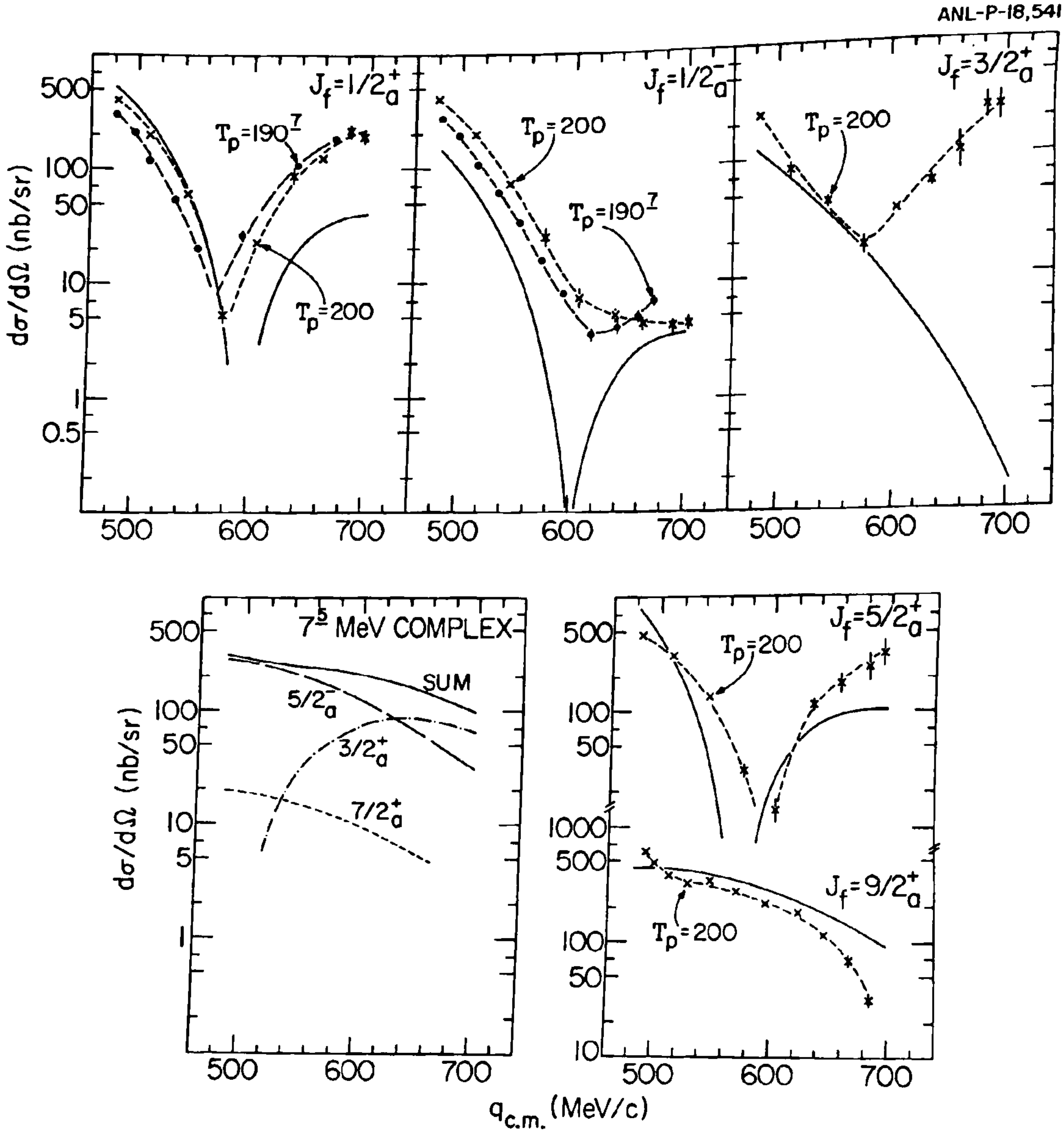

Fig. III-2. Differential cross sections for $^{12}C(p,\pi^+)^{13}C$ compared to calculation. The observed excitation energies in MeV are $1/2_a^+(3.09)$, $1/2_a^-(0.00)$, $3/2_a^-(3.68)$, $5/2_a^+(3.85)$ and $9/2_a^+(9.50)$. The data with 200-MeV protons are from Ref. 1 (crosses) [from F. Soga et al. Phys. Rev. C 24, 570 (1981)] and with 190.7-MeV protons (solid dots) [M. C. Green, Ph.D. Thesis, Indiana Univ., 1983 (unpublished)]. There is a strong transition at about 7.5-MeV excitation. The calculated curves (solid lines) are obtained by multiplying the quantity P(g) by a single normalization constant for all cases.

ization of the cross section is determined by the absorption of the projectile, which is described by an optical potential. Further simplifications can be achieved at higher beam energies, where the eikonal approximation applies, and where the influence of the real part of the optical potential can be ignored.

The effective interactions in a nuclear medium, which are important for determining the energy of the giant Gamow-Teller resonance, are also discussed. The relationship to G-matrix interactions is described and the extraction of empirical interactions is reviewed.

The difference in total strength for β^- and β^+ decay is fixed by a simple sum rule which can be used to constrain the energy of the giant Gamow-Txller resonance with respect to the isobaric analog state. The energy difference can be expressed in terms of the residual isospin and spin-isospin interactions together with a contribution from the spin-orbit potential.

The observed Gamow-Teller strength is generally 40% less than the sum-rule prediction. Two-particle two-hole correlations can shift the strength to higher excitations above the giant Gamow-Teller resonance, where it is difficult to resolve from the background. Hamiltonian diagonalizations in a multiparticle configuration space show that configuration mixing can account for some of the missing strength in the giant Gamow-Teller resonance region. Couplings to subnuclear degrees of freedom may have a comparable effect, but a decisive test is still lacking. The review article has been accepted for publication.

m. **Enhancement of the Relative Spin Response in (p,p') Reactions on Heavy Nuclei** (H. Esbensen, C. Glashausser* and Others)

The relative spin response of heavy nuclei, observed in inelastic proton scattering on heavy nuclei, has a characteristic dependence on the excitation energy. It is suppressed at low excitations and it exceeds the spin-flip probability for free nucleon-nucleon scattering at large excitations. These experimental findings are in qualitative agreement with the surface response model. The isoscalar spin-independent response dominates

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the inclusive (p,p') cross section at low excitations due to the attractive interaction in this channel. The residual interactions in the spin-excitation channels are repulsive and the associated responses are enhanced at excitations higher than the quasielastic peak.

The calculated spin-flip probabilities reproduce the measurements rather well except at the highest excitations above the quasielastic peak. The enhancement at high excitations may be due to configuration mixing, and may be related to the quenching of the Gamow-Teller strength observed in (p,n) reactions. The comparison of the spin-flip data to the surface response model has been submitted for publication.

C. HEAVY-ION INTERACTIONS

(H. Esbensen, S. Landowne, S. C. Pieper, C. Price and Others)

Our heavy-ion studies concentrate on reactions near the Coulomb barrier and the application of coupled-channels techniques to these reactions. The channels considered consist of inelastic states of both the projectile and target and of channels in which a few nucleons are exchanged between the projectile and target. Nuclear structure considerations are clearly important in choosing the channels to include, and we attempt to see the effects of nuclear structure on the measured cross sections. We are active in both developing new techniques for these calculations and applying them to experimental data. These studies led to a number of significant results this year. A detailed analysis of a series of fusion measurements for Si + Ni isotopes identified the importance of both the changing Q values for two-neutron transfers and the changing neutron radii of the Ni isotopes as different projectile-target combinations are considered. Our work on Coulomb-nuclear interference in inelastic scattering has provided rather direct evidence for the energy dependence of nuclear-coupling interactions. In another study of nuclear fission reactions we emphasized the close relationship between the energy dependence and compound-nucleus spin distribution of the cross section. This relationship should be considered when extracting spin distributions by indirect methods from experimental data.

Up to now most coupled-channels studies of fusion have used only first-order coupling schemes. Our study of Ni + Ni systems has indicated the importance of higher-order couplings in medium-mass nuclei. This result has had a significant effect on our choice of future research directions.

Large coupled-channels calculations for heavy-ion reactions are very difficult and time consuming. For this reason it is useful to have more approximate schemes that allow one to study the influence of various factors on the results. We have improved the constant-coupling approximation and also have made extensive use of our earlier observation that the multipolarity of couplings may be ignored.

a. **A Coupled-Channels Analysis of Silicon-Nickel Fusion Reactions** (S. Landowne, S. C. Pieper and F. Videbaek)

We have completed a set of systematic coupled-channels calculations for the series of $^{28,30}Si + ^{58,62,64}Ni$ fusion reactions, taking into account the different deformations of the projectiles, the low-lying excitations of the targets and the important one- and two-particle transfer reaction channels. A good overall agreement is obtained with the data. Detailed variations in the low-energy cross sections are found to be due to the variations in the two-neutron transfer reaction Q-values. An interesting effect revealed by the systematics is a correlation between the fusion cross sections and the variation of the neutron radius of the Ni isotopes predicted by Hartree-Fock calculations. This work is accepted for publication.

b. **Spin Distributions in Heavy-Ion Fusion Reactions** (H. Esbensen, S. Landowne and C. H. Dasso*)

Recently-measured fission fragment anisotropies following the fusion of $^{16}O + ^{232}Th$ have been interpreted as being evidence for anomalously broad spin distributions of the compound nucleus. We emphasize, however, that under rather general considerations, the spin distribution is fixed by the energy dependence of the total fission cross section and, moreover, a limiting, model-independent distribution is predicted at low energies where the cross section drops exponentially. We have applied the coupled-channels formalism to study the fusion of the $^{16}O + ^{232}Th$ system. We have found that the couplings to the strong inelastic excitation channels are sufficient to explain the measured low-energy cross sections. The largest enhancement effects are due to the static deformations of ^{232}Th. In particular, the positive hexadecapole moment plays an important role. We have verified that a simple frozen approximation, where one averages over the orientations of the deformed target, is accurate. The shapes of the spin distribution for the compound nucleus are strongly affected by the static deformations at energies around the Coulomb barrier. A limiting shape, independent of deformations and energy, is reached at very low energies. However, the second moments of the spin distributions are much smaller than the values which have been extracted

*Niels Bohr Institute, University of Copenhagen, Denmark from the measured angular distribution of fission fragments. This discrepancy, together with the fact that the calculations reproduce the energy dependence of the total fission cross sections, indicates that the analysis of the measurements in terms of the decay of a fully equilibrated compound nucleus is inconsistent. In fact it has become clear through our work that transfer-induced fission contributes significantly at low energy and many of the spins involved at higher energies are too large to produce a stable compound nucleus. A comment on this work has been published, and a full paper is accepted for publication.

c. **Higher-Order Coupling Effects in Low-Energy Heavy-Ion Fusion Reactions** (H. Esbensen and S. Landowne)

Conventional coupled-channels calculations which take surface-vibrational degrees of freedom into account in heavy-ion collisions make use of linear coupling schemes. Such calculations have successfully described the low-energy fusion cross sections for relatively light and asymmetric mass combinations. They fail, however, for heavier and more symmetric cases, such as Ar + Sn and Ni + Ni. We have applied a second-order vibrational model to Ni + Ni fusion reactions. It is found that the additional higher-order effects are as important as the linear couplings in determining the low-energy fusion cross section (Fig.III-3). As a result, the agreement with the data is significantly improved. Similar effects should occur for many combinations of medium-heavy nuclei. This work has been submitted for publication.

d. **Improved Approximation for Multi-Dimensional Barrier-Penetration Problems** (S. Landowne and C. H. Dasso*)

The so-called "constant coupling" approximation has provided a valuable insight into the nature of multi-dimensional barrier penetration problems. It has been used in several analyses of heavy-ion fusion reactions. The method consists of diagonalizing the coupled intrinsic system at the position of the unperturbed barrier, shifting the barrier by the eigenvalues, computing the transmissions through the resulting eigen-barriers

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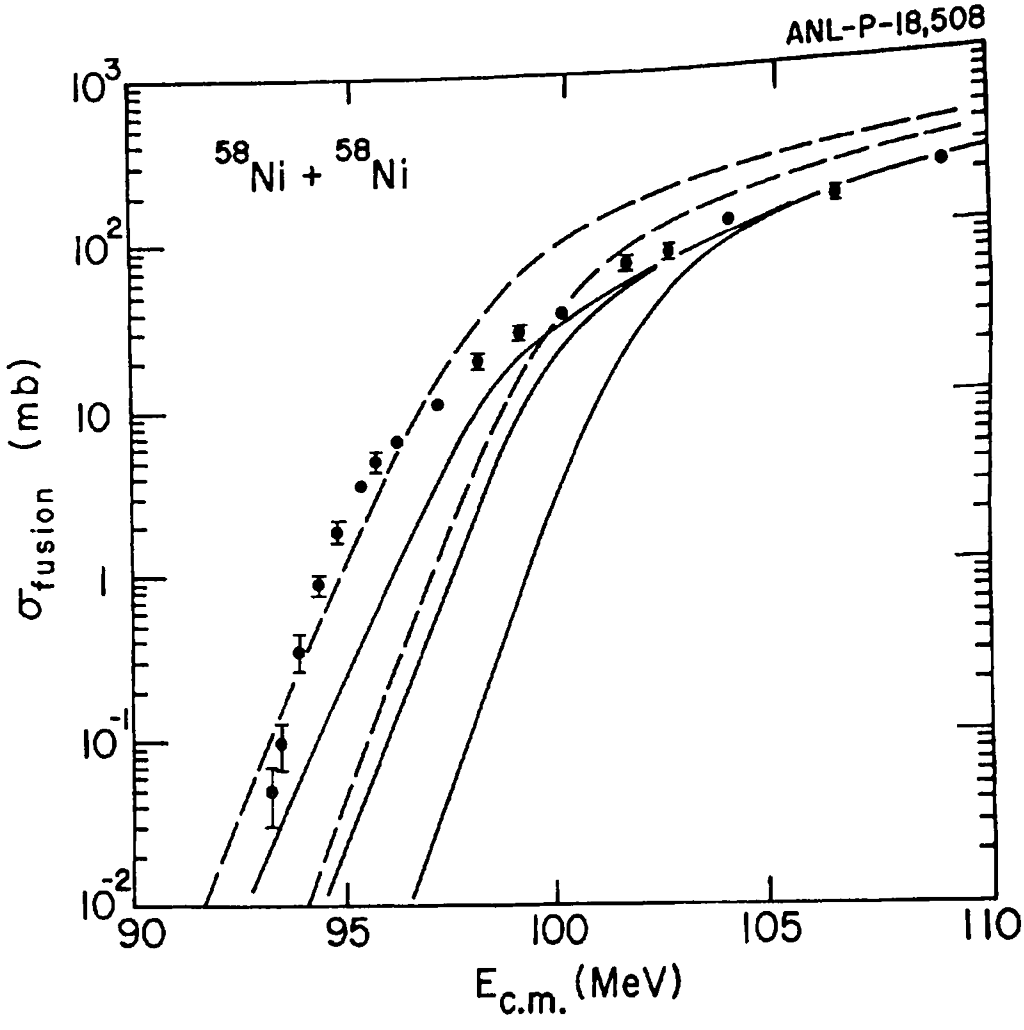

Fig. III-3. Fusion calculations for $^{58}Ni + ^{58}Ni$. The solid curves show, in increasing order, the results of no-coupling, linear coupling and second-order coupling calculations. The dashed curves are the adiabatic limits corresponding to the linear and second-order models.

and weighting them by the overlap of the initial state with the eigenvectors. This method ignores the variation of the coupling interaction in the barrier region. To improve upon it we have considered extending the procedure by carrying out the diagonalization as a function of position, thereby generating the eigenbarriers explicitly, and then weighting the corresponding penetration probabilitites by the overlap factors taken at the position of the unperturbed barrier. This presumes that the variation of the overlap factors in the barrier region can be ignored. It is noted that this prescription contains both the sudden and the adiabatic limits of the exact problem as limiting cases. Our calculations for intermediate situations, as applied to heavy-ion fusion reactions, indicate that the method is reliable for enhancements of the low-energy cross sections up to about three orders of magnitude. We have developed a program which calculates fusion cross sections approximately, but very rapidly, allowing for couplings to surface excitations and other channels. The variation of the coupling is included with negligible extra cost by making a second-order expansion at the position of the barrier. A paper reporting this work has been accepted for publication.

e. **Evidence for the Energy Dependence of Effective Heavy-Ion Interactions** (S. Landowne, C. H. Dasso* and G. Pollarolo†)

Recent studies of low-energy heavy-ion elastic scattering have inferred an energy dependence in the real ion-ion potential. This polarization effect is due to the virtual excitation of inelastic and transfer reaction channels which occurs during the relatively long collision times at lower energies. The general nature of this process suggests that it should be present in other observables. The inelastic cross section at very low energies provides a unique testing ground because it depends directly on the interference between the nuclear excitation amplitude and the known Coulomb excitation amplitude. Our analysis of precise data for $^{16}O + ^{208}Pb$ inelastic scattering in the energy range of 60 to 70 MeV indicates that the nuclear coupling interaction is about twice as large as at 100 MeV. This provides the first evidence for the energy dependence of the effective nuclear coupling interaction in heavy-ion collisions (Fig. III-4). A paper reporting this work has been published.

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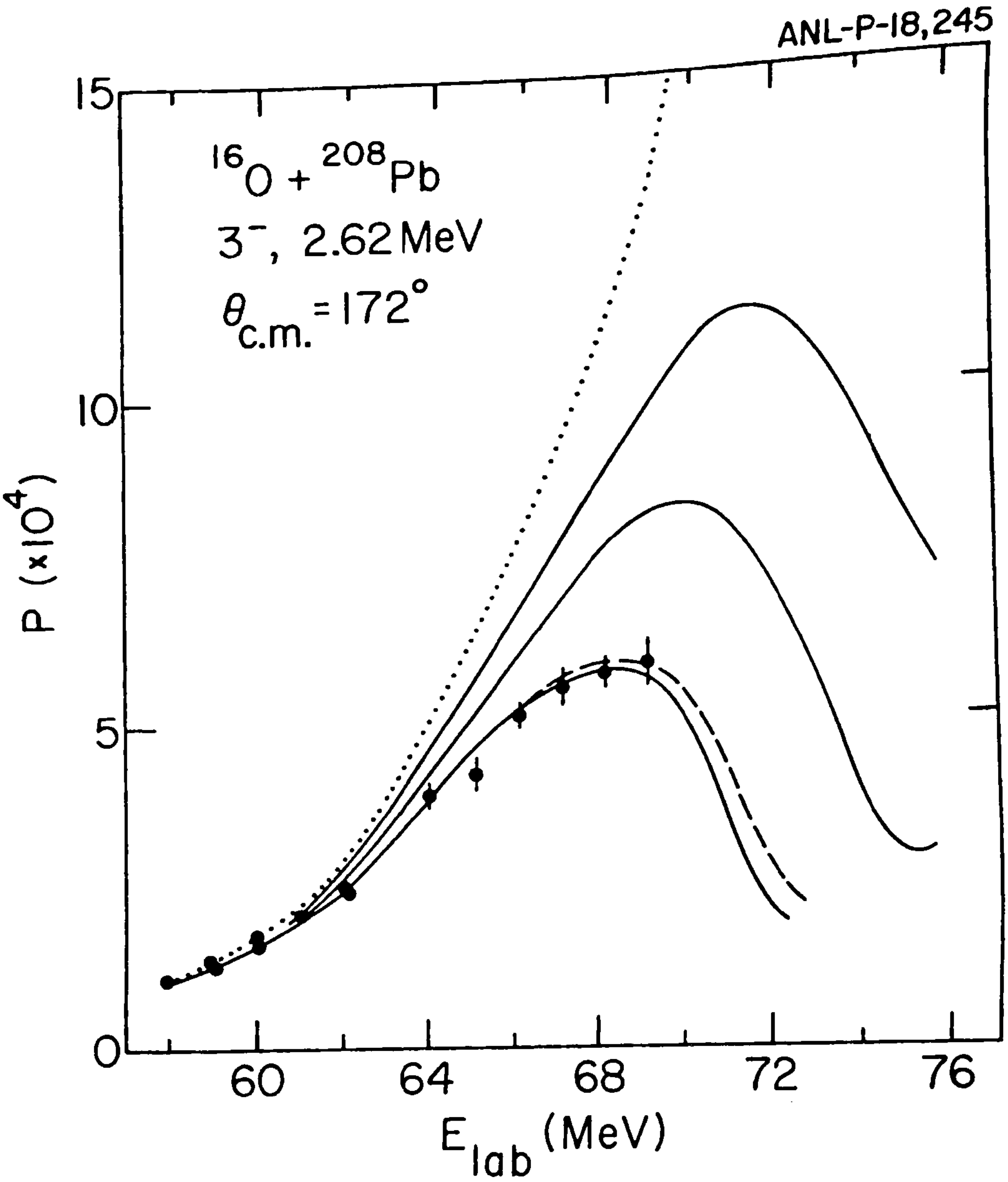

Fig. III-4. Probability for exciting ^{208}Pb in low-energy ^{16}O + ^{208}Pb collisions. The dotted curve results from Coulomb excitation alone. The uppermost solid curve includes nuclear coupling with a fixed strength determined from data at 100 MeV. The fit to the data uses a nuclear coupling that increases linearly as the energy decreases, and is about twice the 100-MeV value at E_{lab} = 68 MeV. The dashed curve is computed with the same couplings but pure Coulomb distorted waves.

f. **Reactions Involving Heavy Deformed Nuclei** (H. Esbensen, S. C. Pieper, S. Landowne, C. Price and B. F. Bayman*)

Two-particle transfer reactions using heavy projectiles on well-deformed nuclei offer, in principle, one of the most direct ways of studying the influence of nuclear rotation on pairing degrees of freedom. Some measurements which study the correlation of particle transfer and high spins have recently been carried out. The fully-quantum-mechanical and microscopic approach to this reaction problem is, however, not feasable. We are making use of simplifications, namely the sudden limit and the macroscopic approach to transfer reactions, to develop a tool which can be applied to the analysis of the data.

In another effort, we intend to incorporate proximity form factors for the interaction of two axially-symmetric deformed nuclei into a full coupled-channels reaction code. This will allow us to study the differences with respect to conventional prescriptions which use interactions directed along the line joining the nuclear centers.

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D. QUANTUM-MECHANICAL VARIATIONAL CALCULATIONS OF FINITE MANY-BODY SYSTEMS

(S. C. Pieper, R. B. Wiringa, V. R. Pandharipande* and Others)

In the last few years we have been developing techniques and programs for quantum-mechanical variational Monte Carlo (VMC) calculations of the ground states of finite many-body systems. Our long-term goal is to be able to calculate the ground states of nuclei. We started with calculations of drops of He atoms which have only a simple central potential. These calculations are now complete.

We have used our VMC wave functions to make a number of interesting studies of properties of the ground states of many-body systems; we believe these studies have relevance to measurements of nuclei.

In 1986 we completed a study of the structure functions of drops of ^{4}He atoms (Bose system) and ^{3}He atoms (Fermi system) and the relationship of the measured structure function to dynamical atom-atom correlations. From this and calculations of the structure functions of nuclear matter and of ^{3}H, ^{3}He and ^{4}He nuclei, we conclude the inclusive electron scattering will be most sensitive to dynamical correlation effects in mass-3 and mass-4 nuclei; in heavier nuclei the dynamical correlations are largely masked by the correlations implied by Fermi statistics.

We are presently completing studies of the momentum distributions and single-atom density matrices in the drops; these studies will also have relevance to electron scattering from nuclei.

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a. **Structure Functions and Correlations in Many-Body Systems**
(S. C. Pieper, R. B. Wiringa, V. R. Pandharipande* and D. Lewart*)

There has recently been a lot of interest in deducing the two-proton distribution function in nuclei by inelastic electron scattering. Inclusive electron scattering can be analyzed to obtain the longitudinal-structure function, $S_L(k)$. The Fourier transform of $S_L(k)$ is related to the two-proton distribution function, $\rho_2(r_{12})$.

We have used our wave functions for ground states of drops of liquid ^{4}He and ^{3}He to compute S(k) and $\rho_2(r_{12})$ for the He drops. In the ^{3}He case we computed S(k) and $\rho_2(r_{12})$ for all pairs of atoms and for just pairs with parallel spins; the later results are comparable to the longitudinal structure function measured by electron scattering which depends only on pairs of protons.

We find that Fermi statistics and the repulsive core in the He-He interaction both have similar effects on S(k) and $\rho_2(r_{12})$ and that these effects are not additive. Thus, in the case of parallel spins for which every pair is subject to Fermi statistics, the dynamical contribution to the distribution function is largely masked by the Fermi statistics as shown in Fig. III-5.

We also computed $S_L(k)$ and $\rho_2(r_{12})$ for nuclear matter using hypernetted-chain calculations and several realistic two-nucleon and three-nucleon potentials. The results are similar to those obtained for the ^{3}He drops; Fermi statistics largely mask any dynamical correlation results.

This work, along with calculations made in Urbana for ^{3}H, ^{3}He and ^{4}He nuclei, has been submitted for publication. The conclusion of the work is that more accurate measurements of $S_L(k)$ for the 3- and 4-body nuclei offer the best opportunity for seeing the dynamical effects of nucleon-nucleon correlations in inclusive electron scattering.

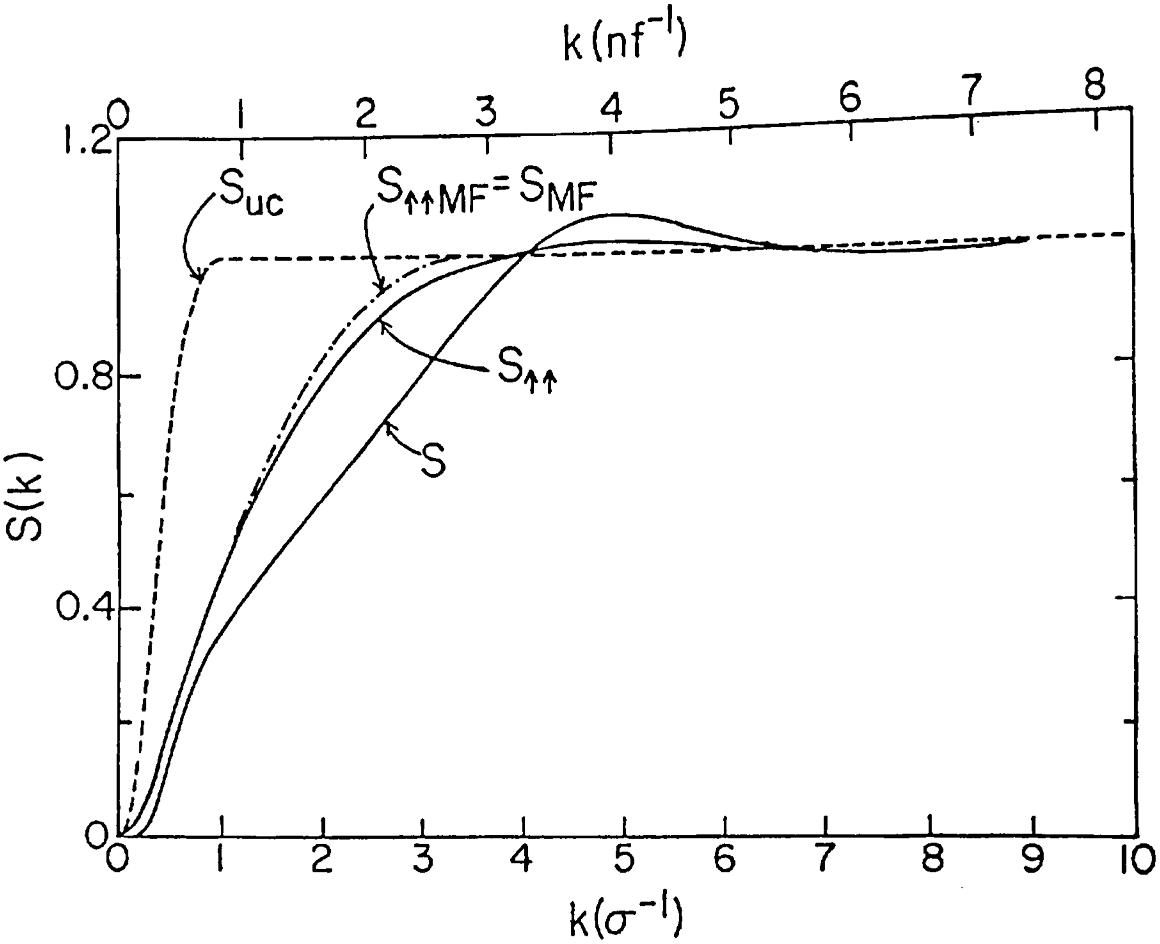

Fig. III-5. The S(k) and $S_{\uparrow\uparrow}(k)$ with dynamic correlations are shown by the full lines; the mean-field value $S_{MF}(k) \equiv S_{\uparrow\uparrow,MF}(k)$ is shown by the dash-dot line, and the uncorrelated (neither dynamic nor statistical correlations) $S_{uc}(k) \equiv S_{\uparrow\uparrow,uc}(k)$ is shown by the dashed line. Results shown are for a 70-atom ^3He drop.

b. **Momentum Distributions and Natural Orbits in Drops of Liquid He**
(S. C. Pieper V. R. Pandharipande* and D. Lewart*)

We have used our ground-state wave functions for drops of liquid ^{3}He and ^{4}He to compute the momentum distribution, $\rho(k)$, of the atoms in the drop, the breakup amplitudes $\rho_{N-1}(k)$ into a single atom and the ground (or low-lying) state of the N-1 atom system, and the single-atom density matrix $\rho_1(\vec{r},\vec{r}')$. Many-body theory provides relationships between these densities which we have been able to investigate. For example, we find that the small-k behavior of $\rho(k)$ in the Bose system is completely determined by $\rho_{N-1}(k)$ rather than by the Fourier transform of $\sqrt{\rho(r)}$ as suggested by mean-field theory. The density matrix can be expanded as a sum of contributions from fractionally-occupied natural orbits. The lowest natural orbit gives $\rho_{N-1}(k)$ for the Bose drops. Contrary to some expectations, the natural orbits for the Fermi drops do not look at all like the lowest eigenfunctions of a potential well; for example, there is no zero-node S-wave natural orbit.

At present we are computing the $\rho_{N-1}(k)$ for the ^{3}He Fermi drops. When this calculation is completed, a paper on all of these results will be prepared. The calculations for the Fermi drops take many hours of Cray XMP time and could not be done with our allotment of ER Cray computer time; about 2/3 of the calculations are being done on the Urbana Cray with NSF funding.

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c. **Elementary Excitations of Liquid ^{4}He Drops**
(R. B. Wiringa, S. C. Pieper and V. R. Pandharipande*)

We have made microscropic variational calculations of low-energy elementary excitations of liquid ^{4}He drops containing N atoms. The calculations have been done for $20 \leq N \leq 240$ with the VMC method, and for $20 \leq N < 10{,}000$ using a local density approximation (LDA) for the pair distribution function. The excitations studied include the J=0 breathing mode and the J=2,3, and 4 surface excitations, as well as the ripplon spectrum of the plane surface.

The excited-state wave function is taken as a sum of single-particle excitation operators acting on the variational ground state. The operators

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include two or three variational parameters and are constructed with the appropriate angular momentum and parity of the excitation. The excited-state energy is computed in the Feynman-Cohen approximation, which should give a good measure of the energy required for one quantum of excitation.

The vibrational energies predicted for drops with $N \lesssim 240$ are significantly smaller than those predicted by the sharp-surface liquid-drop model. The breathing-mode energies have the proper long wavelength (large N) behavior, but the surface and ripplon energies do not, probably as a result of inadequacies on the variational ground-state wave function. We are now investigating whether a "filtering" procedure designed to remove excitations due to paired surface phonons from the trial function can improve these results.

E. NUCLEAR STRUCTURE STUDIES IN DEFORMED AND TRANSITIONAL NUCLIDES

(R. R. Chasman, C. E. Price and Others)

The goal of this program is to understand the strong correlations in nuclear states that are due to the effective two-body interaction. These effects are manifest in strongly-deformed nuclides and can be well treated in such cases through the introduction of deformation into the single-particle potential. In transitional nuclides, however, such an approach is not adequate for obtaining a reasonable description of nuclear states. It is a major challenge of nuclear structure theory to devise methods of treating states that are weakly deformed or very soft vibrators. In our studies we utilize both the deformed single-particle potential methods and correlated many-body wave functions to understand nuclear properties. Our major interests include: (1) the study of strong octupole correlation effects and octupole deformation in the heavy elements, which was first predicted in this research program; (2) the study of the changes in nuclear shapes as a function of angular momentum in the mass 150 region; this includes both the gradual change from spherical to slightly oblate shapes along the yrast line and the possible superdeformed nuclear states in this region; (3) the competition between γ deformation and octupole correlation effects in the mass 220 region; (4) developing new many-body methods for dealing with weakly-deformed nuclear states. With the exception of (4), our research involves a strong collaboration with the experimental programs at Argonne.

In the past year, we have developed a program for calculating nuclear single-particle states in a potential that is both reflection asymmetic (odd multipole deformations) and axially asymmetic (γ deformation) with the option of including angular-momentum cranking as well. This has been done on the ER Cray as very large matrices must be diagonalized in these calculations. This program has been applied to the study of several problems detailed below. At present, we are trying to develop many-body wave functions that exploit the capabilities of the ER Cray computers.

We are also interested in the application of relativistic mean-field theory to deformed nuclei. We have found that the high compressibilities associated with these theories result in too-small deformations.

a. **γ Deformation in a Reflection-Asymmetric Single-Particle Potential** (R. R. Chasman)

We have completed the development of a computer code for calculating single-particle states in a potential that is both reflection asymmetric and axially asymmetric. Because of these asymmetries in the potential, neither parity nor j_z (the projection of angular momentum on some axis) is a good quantum number. Accordingly, rather large matrices ~ 600 × 600 must be diagonalized to obtain enough eigenstates to do a Strutinsky method calculation of energy as a function of deformation parameters. We have used a Cartesian harmonic oscillator basis set for these calculations. We have also included a cranking term in the single-particle potential, which allows us to search for nuclides that might be superdeformed at high spins. We have applied this program to search for γ deformation in the A ~ 220 mass region where octupole correlation effects are known to be important. We have also applied it to the rare-earth region to search for superdeformation at high spins.

b. **γ Deformation in the Mass Region A ~ 220** (R. R. Chasman and I. Ahmad)

We have carried out a theoretical survey of the light actinides to see where γ deformation effects are most likely to be found in conjunction with octupole deformation. The calculations suggest that γ deformation effects are most likely to be found in nuclides with Z ~ 86 if there are sufficient neutrons to deform the nucleus and for N ~ 130, if there are sufficient protons. Specifically, we expect to find large triaxiality effects in the nuclides ^{221}Fr and ^{221}Pa. We have carried out an analysis of gamma-transition rates in ^{225}Ra and ^{223}Ra. Our analysis of interband E2 transition rates indicates a γ deformation of 12° in these nuclides. This study has recently been published.

c. **Superdeformation in the Rare Earth Region** (R. R. Chasman)

In the past few years, we have used our many-body wave functions to study the properties of high-spin slightly-oblate states near the yrast line in nuclides with A ~ 150. The agreement between our calculations and experimental measurements has been extremely good. From these analyses, we obtain a set of spherical single-particle energy levels for proton and neutrons in this mass region. Very recently, superdeformed states (prolate deformations with 2:1 axis ratios) have been observed in high spin ($I > 30$) states of ^{152}Dy. We have used the single-particle level spacings extracted from our studies of the oblate states as input to determine the parameters of Woods-Saxon potentials for protons and neutrons. Using these potentials, in the framework of the cranked Strutinsky procedure, we have searched for other nuclides where superdeformation might be found. In our calculations, we have varied the axially-symmetric quadrupole and hexadecapole deformation parameters, as well as the triaxiality deformation parameter. Our calculations suggest many nuclides that are likely candidates for finding superdeformed states (see Fig. III-6). Several of these nuclides are being investigated by the heavy-ion group at Argonne.

d. **Yrast States in ^{148}Gd** (R. R. Chasman, R. V. F. Janssens, I. Ahmad, T.-L. Khoo, R. Holzmann, W. C. Ma, H. Emling, M. Piiparinen,* P. J. Daly,* Z. Grabowski,* M. Quadder,* M. Drigert† and U. Garg†)

There has been an intensive experimental study of the yrast and near-yrast states of ^{148}Gd made by the heavy-ion group at Argonne. We have applied our many-body wave functions to a study of this nuclide to see how well, and to how high a spin, it can be understood with this approach. We find that our calculations agree well with the experimental findings up to a spin slightly above $I = 40$. There are some deviations between our calculations and the observed yrast spectra at higher spins. This may signal the onset of triaxiality in this nuclide.

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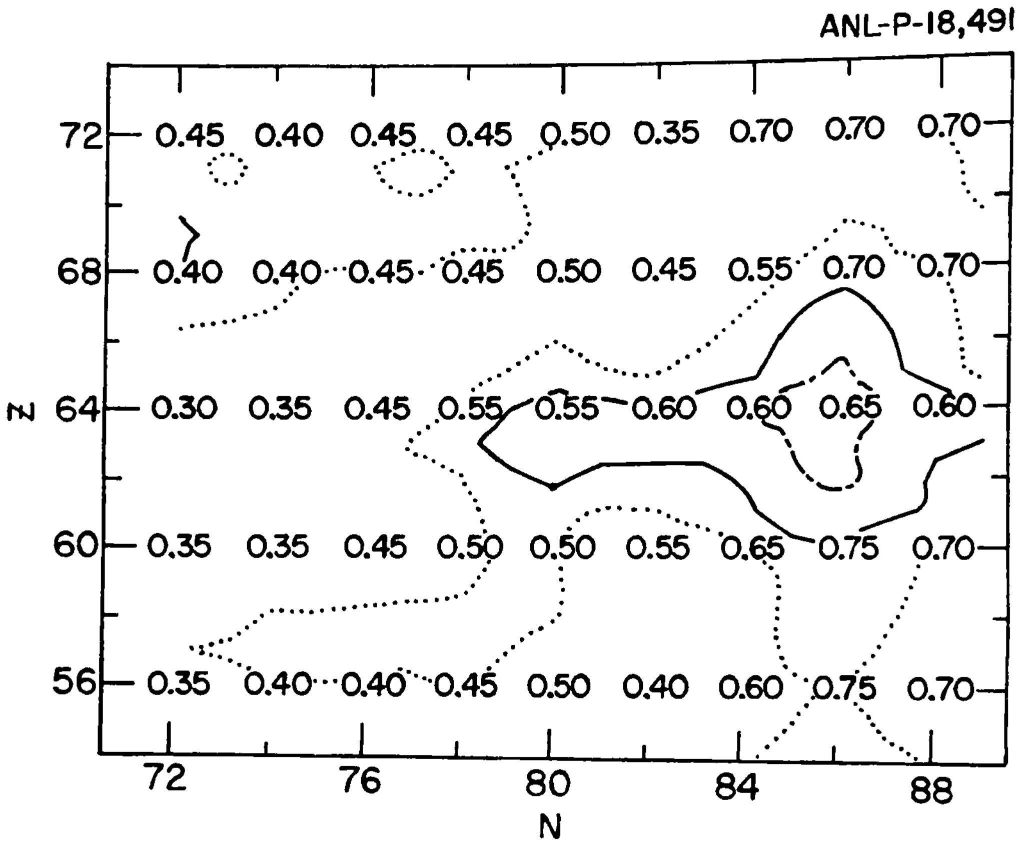

Fig. III-6. Contour plot of $(WD)_{50}$, the well depth at I = 50, as a function of Z and N. The numbers given in the figure are the quadrupole deformation parameter ν2. The dotted curve is the 1-MeV contour, the solid the 2-MeV contour, and the dash-dot the 3-MeV contour.

e. **Octupole Correlations in ^{227}Ac** (R. R. Chasman, H. Martz,* G. L. Struble,* D. Decman,* R. Sheline,† R. Naumann‡ and D. Burke§)

^{227}Ac is one of the few nuclides with strong octupole correlation effects, that can be populated in one-nucleon transfer reactions. We have carried out an angular momentum decomposition of the single-particle states in a potential with octupole deformation to analyze the proton transfer data. We have also carried out many-body calculations of the parity projected $3/2^{\pm}$ ground state and $1/2^{\pm}$ excited-state bands in this nuclide. These calculations indicate that the 1/2 bands are not octupole deformed while the 3/2 bands are. The study of ^{227}Ac is being written up at present.

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f. **Relativistic Hartree Description of Deformed Nuclei Including Vacuum Fluctuation Corrections and Non-Linear σ-Meson Couplings** (C. E. Price and R. J. Furnstahl*)

The importance of non-linear scalar couplings and vacuum fluctuation corrections in a relativistic mean-field description of nuclear structure is investigated by considering the equilibrium deformations of non-spherical nuclei. Although the σ-ω mean-field model has provided a good description of nuclear structure for spherical nuclei, including the spin-orbit splitting of the levels, one shortcoming of this model is its overestimation of the nuclear compressibility. When extended to calculations in deformed nuclei, this high compressibility results in equilibrium deformations that are approximately a factor of two smaller than expected from experimental measurements of nuclear quadrupole moments. Fox and Serot are currently investigating the effects of vacuum fluctuation corrections and non-linear σ-couplings in spherical nuclei, and they have found that the model parameters (the σ-meson mass and the meson coupling constants) may be adjusted to reproduce the structure of spherical nuclei with a smaller compressibility. We are using the results of their work to determine whether the parameters obtained from spherical nuclei are able to reproduce the equilibrium deformations of non-spherical nuclei and to investigate the possibility of using deformed nuclei to constrain the values of the model parameters.

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F. BINDING ENERGIES OF HYPERNUCLEI AND Λ-NUCLEAR INTERACTIONS

(A. R. Bodmer and Q. N. Usmani*)

Studies of the binding energies of hypernuclei and their interpretation in terms of Λ-nuclear interactions have been continued. In particular, during the past year a study of α-cluster hypernuclei with one- and two-Λ hyperons has been made. The results for the hypernucleus $^{9}_{\Lambda}Be(\equiv 2\alpha + \Lambda)$ confirm the existence of strongly-repulsive ΛNN three-body forces which were previously found to be required for an adequate description of the binding energies of the s-shell hypernuclei and of a Λ in nuclear matter. The results for ΛΛ hypernuclei show that the force between two Λs is quite strongly attractive, about equally so as the comparable force between two nucleons. The role of more complicated NN potentials, such as tensor potentials will be investigated.

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a. **The α-Cluster Hypernuclei $^{5}_{\Lambda}$He, $^{6}_{\Lambda\Lambda}$He, $^{9}_{\Lambda}$Be, $^{10}_{\Lambda\Lambda}$Be and Hypernuclear Interactions** (A. R. Bodmer and Q. N. Usmani*)

Variational calculations for $^{6}_{\Lambda\Lambda}$He, $^{9}_{\Lambda}$Be and $^{10}_{\Lambda\Lambda}$Be have been made with α-cluster models: $^{6}_{\Lambda\Lambda}\text{He} \equiv \alpha + 2\Lambda$, $^{9}_{\Lambda}\text{Be} \equiv 2\alpha + \Lambda$, $^{10}_{\Lambda\Lambda}\text{Be} \equiv 2\alpha + 2\Lambda$. The αα potentials used fit the experimental αα scattering. Various αΛ potentials $V_{\alpha\Lambda}$ are considered, all of which reproduce $B_{\Lambda}(^{5}_{\Lambda}\text{He})$. Some of the $V_{\alpha\Lambda}$ are obtained from an α-Λ model of $^{5}_{\Lambda}$He by a folding procedure using effective ΛN and ΛNN forces; realistic $V_{\alpha\Lambda}$ are also obtained from 4N-Λ Monte Carlo (MC) variational calculations of $^{5}_{\Lambda}$He. These MC $V_{\alpha\Lambda}$ include many-body effects which give a central hump even with only ΛN forces. We find that $^{9}_{\Lambda}$Be is overbound by more than one MeV with use of realistic αα and αΛ potentials, even with reasonable estimates of ΛN exchange effects which give a reduction ≈ 0.5 MeV. Repulsive dispersive ΛNN forces which can account for the overbinding of $^{5}_{\Lambda}$He give rise to a repulsive three-body ααΛ potential which when included brings the calculated $B_{\Lambda}(^{9}_{\Lambda}\text{Be})$ into good agreement with the experimental energy. Thus our results for $^{9}_{\Lambda}$Be support the existence of strongly repulsive ΛNN forces which were needed in our studies of the s-shell hypernuclei and of the well depth (F.b.).

The ΛΛ interaction strength is obtained for a number of ΛΛ potential shapes from our calculations of $^{6}_{\Lambda\Lambda}$He and $^{10}_{\Lambda\Lambda}$Be. The ΛΛ interaction obtained from the well-established $^{10}_{\Lambda\Lambda}$Be event is found to be quite strongly attractive, quite similar to the comparable $^{1}S_{0}$ NN interaction (after one-pion-exchange has been subtracted) with correspondingly large negative ΛΛ scattering lengths of ≈ −4 to −5 fm. We find with the ΛΛ interaction strengths obtained from $^{10}_{\Lambda\Lambda}$Be that $^{6}_{\Lambda\Lambda}$He is underbound with respect to the experimental binding energy by more than one MeV for all our αΛ and ΛΛ potentials.

A preliminary version of this work was reported in an invited paper at the 11th Int. Conf. on Few Body Systems in Particle and Nuclear Physics. This paper also has a discussion of the implications of ΛΛ hypernuclei for the H dibaryon. In particular, it is pointed out that the observation of the $^{10}_{\Lambda\Lambda}$Be hypernucleus permits an H dibaryon which is bound, but by less than about 20 MeV with respect to two Λs. The possiblity of bound H-nucleus states is also discussed.

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We are continuing variational calculations of ${}^{9}_{\Lambda}$Be with better allowance for the angular momentum dependence of the $\alpha\alpha$ potential. In particular, we are also calculating the energy of the lowest excited (doublet) state built on the first J = 2+ state of ^{8}Be. Preliminary calculations indicate an excitation energy of ≈ 3 MeV, consistent with experiment, implying that the state is particle stable (with respect to breakup into ${}^{5}_{\Lambda}$He + α at a threshold 3.5 MeV above the ground state) and that it should decay by γ transition to the ground state.

b. **Binding Energies of the s-Shell Hypernuclei and the Λ Well Depth**
(A. R. Bodmer and Q. N. Usmani*)

In this work variational Monte Carlo calculations have been made for the s-shell hypernuclei, and the Λ binding energy in nuclear matter (the well depth) has been calculated variationally with the Fermi hypernetted chain method. A satisfactory description of all the relevant experimental Λ separation energies and also of the Λp scattering is obtained with reasonable central two-pion-exchange ΛN and ΛNN forces and strongly-repulsive dispersive ΛNN forces. For the latter both spin-indedpendent and spin-dependent forms were considered with the spin-dependent form preferred. Such a spin dependence of the ΛNN force reduces the spin dependence of the two-body ΛN force by ≈ 1/3, and correspondingly contributes ≈ 1/3 to the 0^{+}-1^{+} splitting of the A = 4 hypernuclei. However, even this reduced ΛN spin dependence is quite appreciable and significantly larger than the most commonly accepted values. On the more technical side, a significant feature is the important ΛNN three-body correlations required by the two-pion-exchange ΛNN force in the s-shell hypernuclei.

A paper with the above title is almost completed for publication. A preliminary account of this work was presented as an invited paper and has been published.

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G. QUANTUM MECHANICS WITH MAGNETIC CHARGES OR FLUX LINES

(M. Peshkin and H. J. Lipkin*)

This work is part of an ongoing investigation of the elementary quantum mechanics of systems containing both electric and magnetic charges. Past results of this program include: the most general derivation of the Dirac charge quantization law $eg/c=n\hbar/2$, independently of any assumptions about vector potentials, singular or otherwise; analysis of the angular momentum in the electromagnetic fields when both kinds of charges are present, with peculiarities at large and small distances that constrain the theory in significant ways; the identification of a singularity at the points where electric and magnetic charges coincide, which has very general consequences for all monopole theories; and an analysis of the angular momentum of cyons, "atoms" consisting of an electron bound to a magnetic flux line.

a. **Physics with Magnetic Charges and Electric Currents**
(M. Peshkin and H. J. Lipkin*)

In 1986 we considered the physics of a magnetic charge moving in a magnetic field produced by electric currents instead of by electric charges. Such a system presents no important obstacle to treatment by Newton's laws. However, when we attempt a Hamiltonian description, as is needed for quantum mechanics, we find paradoxes related to, but different from, those appearing in theories with magnetic and electric charges. The resolution of these new paradoxes in a simple-model system yields new information about the physics when both kinds of charges and currents are allowed.

Our model consists of a single magnetic charge constrained to move on a circle surrounding a wire that carries an electric current and thereby serves as the source of a magnetic field acting on the magnetic charge. The Hamiltonian theory works properly as long as the sources of the electric current are included in the dynamics. However, the limiting case corresponding to an externally-fixed magnetic field cannot be described by a sensible Hamiltonian. The motion of the magnetic monopole depends upon non-local variables instead of upon the local magnetic field, and there are troubles with the conservation of energy. There does not seem to be an adequate basis for forming a quantum field theory, at least in the conventional way. One can get out of these troubles by attaching the monopole to a string which serves to count the number of times the monopole has circled around the electric current. This string resembles the Dirac string, but ours is not assumed to carry any magnetic flux or to be involved with any singular vector potential. It simply serves to change the topology of the dynamical system. With the aid of this string, one can introduce a sensible Hamiltonian which is local in the same sense as is classical electromagnetic theory, and which conserves energy. It appears that this topology may be related to that which Yang and Wu found in quite a different way for the classical monopole problem, but we are not now able to explain that connection.

When the theory is quantized, the unphysical feature of a string attached to the magnetic charge can be removed by making use of the fact that quantum mechanical amplitudes depend only upon $\exp[(i/\hbar)\int L dt]$, L being the Lagrangian. However, that can be done if and only if q(t), the time integral

*1985-86 Argonne Fellow, on leave from the Weizmann Institute of Science, Rehovot, Israel of the current around which the magnetic charge g circles, obeys $q(t)=n\hbar/(2g)$ for all times t. This is formally the same as Dirac's quantization law, but the meaning is different because here q is the time integral of a continuous dynamical variable, the current. The charge e in Dirac's law is a constant in the Lagrangian.

This quantized integrated current may serve as a model for the quantized charge on a particle. Let the current-carrying wire be semi-infinite, so that the integrated current appears as a charge at the end. Then the quantization of the integrated current is the quantization of a localized charge.

This work has been published[1] and it was reported by one of us (MP) at the Second International Symposium on Fundamental Questions in Quantum Mechanics in Tokyo.

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[1] H. J. Lipkin and M. Peshkin, Phys. Lett. B179. 109 (1986).

IV. SUPERCONDUCTING LINAC DEVELOPMENT

R. Benaroya, J. M. Bogaty, L. M. Bollinger, P. Markovich, R. C. Pardo, K. W. Shepard, G. P. Zinkann, B. E. Clifft,* J. M. Nixon,* and M. F. Waterson*

INTRODUCTION

Superconducting linac development at Argonne consists of a broad range of activities now guided by remaining questions about the technology of ATLAS and especially by the new requirements for the planned positive-ion injector for ATLAS. Most of the work falls within the following topics: (a) superconducting accelerating structures, (b) electron cyclotron resonance heavy-ion source, and (c) time-of-flight technology for pulsed beams.

Until late in 1986, this program was carried out jointly by the Chemistry and Physics Division. Since then, the program has been managed entirely by the Physics Division, although several members of the Chemistry Division continue to be involved in the work.

A. The Positive-ion Injector for ATLAS

1. Plans for the Positive-ion Injector

Detailed plans for the positive-ion injector for ATLAS have been developed during the past year, and these plans are being vigorously implemented. The objective of the project is to replace the present ATLAS injector, a tandem electrostatic accelerator and its negative-ion source, with a positive-ion source and a new form of superconducting injector linac. This new approach is expected to increase the beam intensity by two orders of magnitude for all ions and lead to a system that will enable ATLAS to accelerate uranium beams of good quality and intensity. We believe that this uranium upgrade will give ATLAS unique capabilities for nuclear research with heavy projectiles having energies in the neighborhood of the Coulomb barrier.

The layout of the positive-ion injector is shown in Fig. IV-1. The positive-ion source for the new system will be an electron cyclotron resonance (ECR) source on a 350-kV voltage platform. Both mass analysis and a first stage of bunching will be carried out on the voltage platform. A second-stage buncher will be added in front of the linac, at ground potential. The source, which will be ready for testing by late summer of 1987, will be the first ECR source operated at high potential.

*Chemistry Division, ANL.

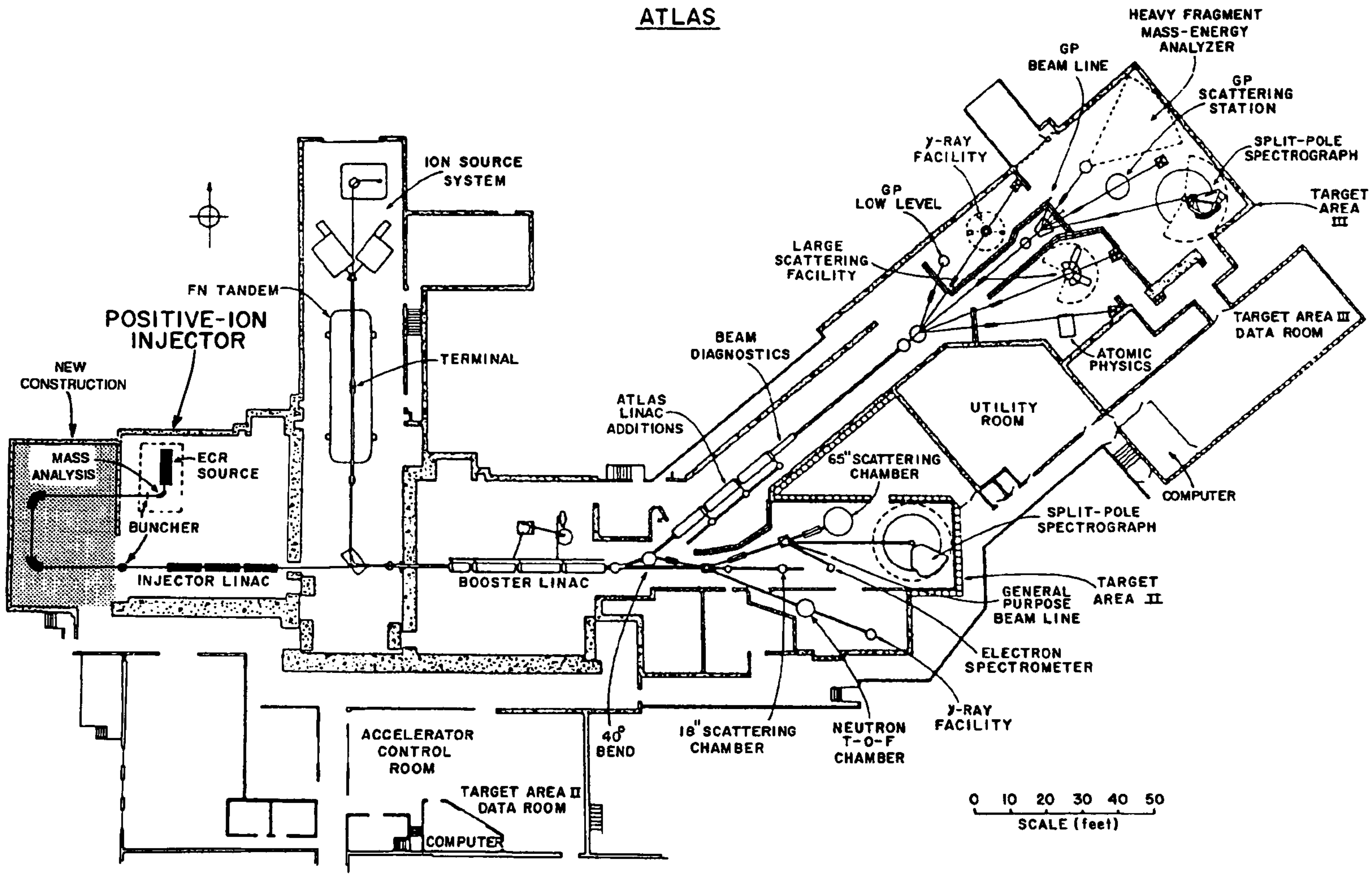


Fig. IV-1. Layout of the positive-ion injector in relationship to the present ATLAS. The figure shows the Phase III injector linac with three cryostats. The Phase I linac, to be completed in 1988, will have only one cryostat.

The injector linac being built to accelerate the low-velocity ions from the ECR source will consist of an array of four different kinds of independently-phased superconducting structures, all having 4 accelerating gaps formed by 3 drift tubes, as shown in Fig. IV-2. These four classes of units are sized to be optimum for projectiles with relative velocities β of 0.009, 0.015, 0.023, and 0.037. The first three of these types will operate at 48.5 MHz and the last type will operate at $3/2 \times 48.5 = 72.75$ MHz. In total, the injector linac will have 18 resonators.

Construction of the positive-ion injector will be carried out in three phases. In Phase I, the goal is to build a small but useful prototype system consisting of a 3-MV linac and an ECR source on its voltage platform. The linac will have just 5 resonators, all but one of which are being built as prototype units. The overall length of the linac will be only 10 ft. Because of the high charge state of ions from the ECR source, even this tiny system will be superior to the present FN-model tandem as an injector for ions with $A > 40$ and will be vastly superior for two classes of ions: (a) those (such as calcium) that are difficult to make with a negative-ion source and (b) those with $A > 80$. Phase I will be completed in late 1988 or early 1989 with funds that have already been allocated to the project.

Because of its limited accelerating power, the Phase I linac will be useful only for ions with $A < 130$. In Phase II, this upper limit will be extended to $A = 190$ by the addition of seven more resonators. The availability of energetic ions in the upper half of the periodic table will greatly strengthen most of the experimental program by making it feasible to use inverse reactions (heavy projectiles on light targets).

In Phase III, the objective is to enlarge the linac enough so that uranium ions can be accelerated up to the velocity ($\beta > 0.045$) required for acceptance by ATLAS. This will be done by adding six more resonators with funding provided during 1989 and with the goal of completing the work by late 1990. The resulting 12-MV injector will enable ATLAS to provide high-quality uranium beams up to energies of about 8 MeV/A. In view of the good beam quality, high intensity, easy energy variability, and continuous (CW) character of these beams, ATLAS will be the ideal machine for the study of nuclear phenomena involving very heavy projectiles near the Coulomb barrier.

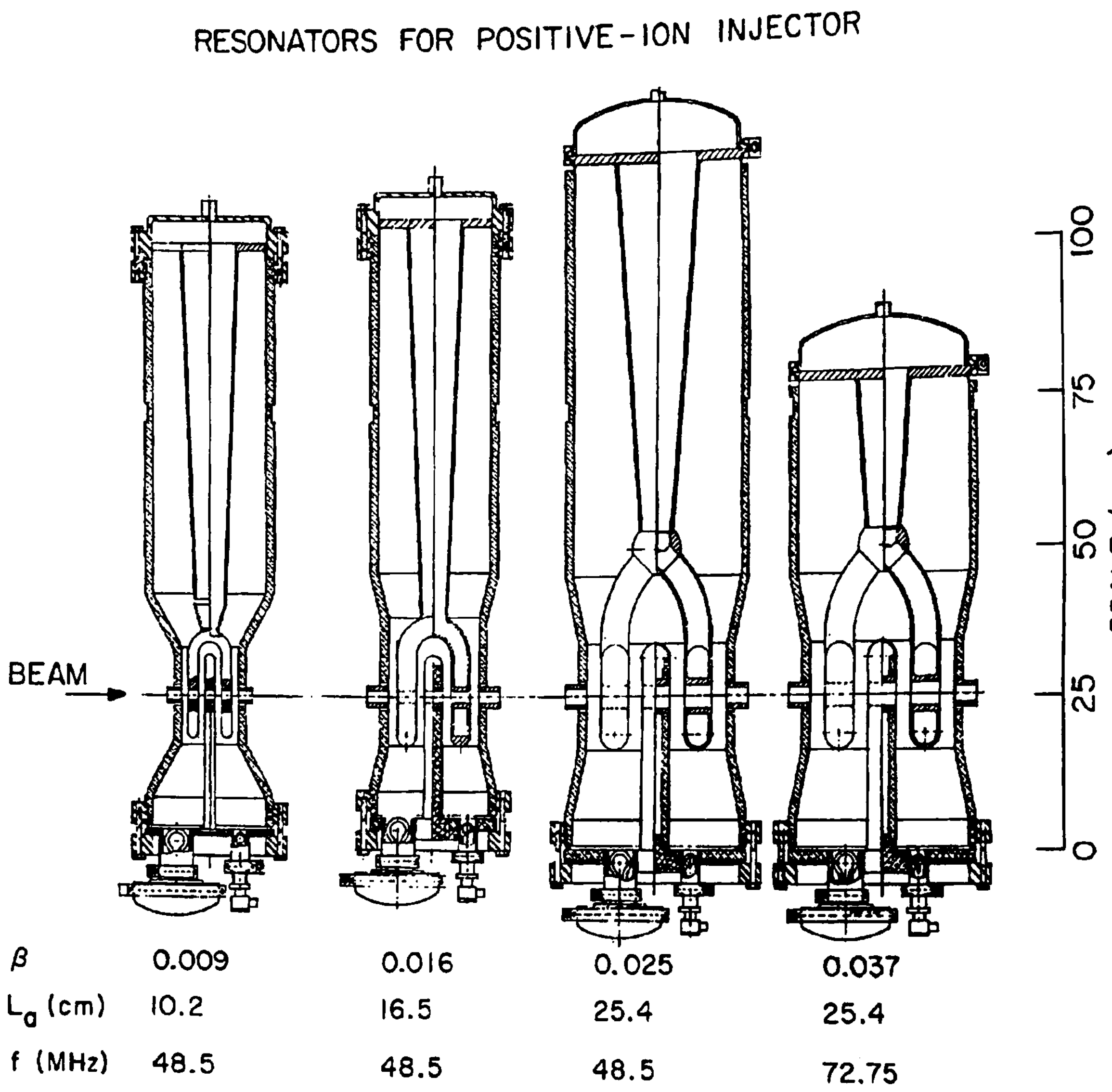


Fig. IV-2. Cross sections of the four types of superconducting resonators used in the injector linac. Each unit consists of a quarter-wave line that drives two drift tubes which, along with a third, ground drift tube, form four accelerating gaps.

A primary requirement for the postive-ion injector is to provide output beams with quality that is as good or better than that of beams from the present tandem injector. Realistic ray-tracing calculations carried out during the past year have shown that this requirement can be met. An important advantage for the injector linac is that it does not suffer the beam-quality deterioration associated with the stripping foil in the tandem terminal.

Work on the positive-ion injector is proceeding on a broad front, including construction of the ECR source and its voltage platform, resonator development, cryostat design, cryogenic-system design and fabrication, improvements in phase-control technology, and building modifications. The discussion that follows emphasizes those topics of most general interest: resonator development and the ECR source.

2. The ECR Heavy-ion Source

The design of the electron cyclotron resonance ion source (ECRIS) and its voltage platform has been completed, and the procurement and fabrication of components is well advanced.

The ECRIS is to be a general-purpose source capable of providing all kinds of ions. In order to meet our needs it must produce beams with relatively high charge states ($0.1 < q/A < 0.5$), good transverse emittance, and small energy spread. These objectives are consistent with the performance characteristics of other ECR sources, some of which have had an important impact on our design. Our goal is to build a source that compares favorably with these existing general-purpose sources with respect to charge-state distribution and beam current.

A special requirement on the source is that it must be operated on a 350-kV voltage platform in order to be able to achieve good bunching and proper matching of the beam into the injector linac. Consequently, the source must be designed in such a way that power consumption is minimized without compromising source efficiency and flexibility. This will be the first ECR source that has been installed on a voltage platform.

A major goal is to build a source that is able to function well for nearly all ions, especially materials that are normally solids. As a result, the plasma chamber has been designed to provide convenient access. It is assumed that, when the source is operational, it will be necessary to devote considerable effort to the development of techniques for the use of solid-feed material.

The main parameters of our ECRIS are given in the following table.

Parameters of the ECRIS for ATLAS

Magnetic Field		
	Peak on Axis	4.8 kG
	Solenoid Magnet Power	33 kW
	Solenoid Current	500 Amp
	Mirror Ratio	1.75
	Mirror Ratio Range	±0.2
	Length of Mirror	46 cm.
	Hexapole Material	Nd-Fe
	Number of Poles	12
	Hexapole Field at Chamber	4.7 kG
RF System		
	Frequency	10.5 GHz
	RF Power	2.5 kW
	Independent Control	both stages
Dimensions		
	Solenoid ID	22 cm.
	Solenoid OD	54 cm.
	Hexapole ID	12 cm.
	Hexapole Length	49.5 cm.
	Anode Aperture	8 mm
	Extraction Aperture	10 mm

The total power required for the source and beam-transport elements on the voltage platform will be approximately 80 kW. Of this, about 50 kW will be dissipated into a liquid-cooling system. In order to preserve the small energy spread of the source, every effort will be made to achieve exceptionally good voltage stability for the voltage platform, hopefully better than one part in 10^4.

The voltage platform is now being assembled in the area where it will be installed, and major components of the source will soon be delivered. Assembly of the system will continue until mid 1987; and the first beams from the source are expected before the end of the summer.

As soon as the ECR source is operable it will be put to use: first for tests of operating characteristics and then for atomic physics experiments on highly-stripped ions. Thus, the operation of the source will be thoroughly developed before beams are needed for the injector linac in late 1988.

3. Superconducting Accelerating Structure for Low-velocity Ions

This activity is concerned with the development of the four new types of 4-gap resonators required for use in the positive-ion injector.

The 48.5-MHz, $\beta = 0.009$ Structure

This structure was designed for use at the input of the injector linac, where the ion velocity may be as small as $\beta = 0.008$. The exceptional performance of this unit, which has been operated at an accelerating field as high as 10 MV/m, was discussed in last year's report. This prototype unit is now ready for use in the injector linac.

The 48.5-MHz, $\beta = 0.015$ Structure

Fabrication of the $\beta = 0.015$ structure was completed in 1986. During testing, it operated with a maximum accelerating field of 6.5 MV/m and at 4.5 MV/m with a power dissipation of 4 W, performance that is substantially better than the 3.0 MV/m field that has been assumed for on-line operation. Also, we have demonstrated that the unit is rigid enough mechanically that the RF frequency variations are not large, and hence we expect to be able to achieve phase control with the voltage-controlled reactance used on the ATLAS split-ring resonators.

Testing of the $\beta = 0.015$ prototype has now been completed and the unit is ready for use in the injector linac.

c. The 48.5-MHz, $\beta = 0.025$ Structure

Fabrication of the prototype $\beta = 0.025$ unit is in progress. The 10-inch length of this structure along the beam direction is large enough that, unlike the units with $\beta = 0.009$ and $\beta = 0.015$, it is now feasible to use fabrication techniques that are similar to those used on the split-ring resonators. This similarity is expected to reduce costs to a significant extent. Also, these fabrication techniques permit design parameters such as β and especially the RF frequency to be changed to some extent without major developmental effort.

Initially, one of the worries about the $\beta = 0.025$ unit was the possibility that it would not be stable enough mechanically. Consequently, extensive tests have been carried out on realistic room-temperature models. The results obtained indicate that the RF-frequency variations of the niobium unit will not be excessive. Consequently, we are confident enough about the success of the $\beta = 0.025$ resonator that the two units required for Phase I are being built simultaneously, thus advancing the schedule and reducing costs. The first of these two units is expected to be ready for testing by August 1987.

The 72.75-MHz, $\beta = 0.037$ Structure

Initially, we had planned to use an RF frequency of 48.5 MHz for this final class of resonator, and the main question was whether to use a 2-gap or a 3-gap structure. However, both of these possibilities looked somewhat unattractive because the quarter-wave line required for 48.5 MHz would be so long as to cause problems in the design of the cryostat. This problem has now been removed by a decision to use a 4-gap structure with an RF frequency of $3/2 \times 48.5 = 72.75$ MHz. Then, for the desired β of about 0.037, one can use both the same housing and the same drift-tube assembly as are being developed for the $\beta = 0.025$ unit. This dual use of these primary components will greatly reduce the cost and effort required to develop and build $\beta = 0.037$ resonators. Construction of the one $\beta = 0.037$ unit required for Phase I will be started in mid 1987.

The decision to use a frequency of 72.75 MHz for one set of resonators implies that the maximum beam-pulse frequency will be 24.25 MHz rather than 48.5 MHz. All users have been informed about this limitation and none has expressed any objection. Indeed, most users want an even lower beam-pulse frequency.

4. Outline of Other Progress on the Injector Linac

The design of a cryostat to house the five resonators for Phase I is well advanced. Fabrication of the cryostat will start in mid 1987.

Installation of the refrigerator required to cool the injector linac is scheduled for September 1987. The helium-transfer components required for this installation are being fabricated.

The design of a helium distribution system for the linac is underway.

Work has started on the design modifications required for the RF control electronics. A prototype RF amplifier has been built and tested.

The good progress being made on upgrading the fast tuner required to control the resonator RF phase is outlined below in Sect. B.

B. Improvements of ATLAS Technology

Although ATLAS is being used routinely and effectively for research, we are continuing to perfect all aspects of the technology. Since much of this work consists of implementing well-established ideas, most of the subject is treated in Sect. V. However, work aimed at upgrading the performance of the voltage-controlled reactance (VCX) used as a fast tuner for the resonators is discussed here because it requires the development of new technology that may be of general interest.

Each VCX involves the rapid switching of a parallel set of high-power PIN diodes that are cooled by liquid nitrogen. This device has operated satisfactorily on ATLAS and it could be used on the injector linac. However, the present VCX (each of which is designed to operate with a reactive power of

5 kW) is being used at its limit of performance, and thus we want to increase its lifetime, reliability, and tuning capacity. We are seeking to achieve these improvements with a modified design in which the power dissipation is reduced and the cooling of the PIN diodes is improved by using bare chips that are immersed in liquid nitrogen. Also, the pulser of the PIN diodes has been redesigned around more advanced components.

Tests of prototypes of the modified VCX and its pulser have shown that performance has been improved substantially. This result suggests that the new fast tuner will soon permit the accelerating fields of some resonators in ATLAS to be increased significantly. Also, the improved tuner will be available for use in the injector linac.

C. Time-of-flight Technology

There is a continuing effort to refine the time-of-flight techniques made possible by the good characteristics of the ATLAS beam. There are two aspects to this work. One is an effort to understand the factors that determine the phase-space area of the output beam. Since this area is the factor that limits the time or energy resolution that can be achieved by bunching or rebunching, respectively, a better understanding of the output beam is expected to lead ultimately to better resolution.

The second aspect of the work is to solve the various practical problems involved in using highly-bunched beams, including upgrading the rebunching resonator, maximizing the long-term energy stability of the linac, and learning to tune the linac so as to obtain the best time resolution. Pulse widths as narrow as 120 psec have been obtained on target for long experimental periods. Although this performance is setting the standard in the field, it is believed that there is still room for improvement.

D. Future Plans and Schedule

In late 1987, the ECR source will be assembled on its voltage platform, and testing will have started. For the linac, four of the five required resonators will have been completed or be nearing completion, fabrication of the cryostat will be underway, prototypes of most control devices will be on hand, the additional (third) refrigerator will be almost installed, and the design of the helium distribution system will be complete.

A major goal for 1988 is to test thoroughly the ECR source by operating it under a wide variety of conditions, including the generation of many different kinds of ion beams. The development of techniques for making and controlling beams from metals will be emphasized. Also, since the quality of the beam from the source may have an impact on the quality of the ATLAS-output beam, the energy spread and emittance of the beam from the source will be studied. As part of the effort to ensure that the ECR source will operate reliably when it is coupled to ATLAS, until late 1988 the source will be used on a part-time basis for atomic physics research.

A key milestone in the development of the technology for the injector linac is an off-line test of one of the new resonators with all of its on-line auxiliary components attached: i.e., RF input, pick-up probe, fast tuner, slow tuner, and the normal control electronics for these devices. This fully-dressed test is being planned for late 1987. The test is designed to identify any remaining problems before the fabrication of the main batch of auxiliary comonents is started.

Assembly of the Phase I (3-MV) linac will start in mid 1988, with the objective of having the linac ready for testing in late 1988. The critical path in this effort is completion of the cryostat, not resonator construction.

Serious work on the beam lines and bunching system required for the positive-ion injector will start during the second half of 1987, after the ECR source has been completed. The only significant technical problem in this phase of the work is the bunching system, and we believe that we have a good concept for it.

Work on the components for the Phase II injector will be started as soon as funding is available in FY 1988. The main tasks will be the fabrication of the required resonators and their cryostat. The fabrication of these Phase II components is not expected to be in conflict with fabrication for Phase I components.

The Phase I (3-MV) positive-ion injector will be installed on line in late 1988, and beam-acceleration tests will be undertaken as soon as the installation has been completed. These initial beam tests will not need to interrupt the operation of ATLAS in its present form. It is expected that these tests will be completed by early 1989, and then the positive-ion injector will immediately be coupled to ATLAS. We expect that the Phase I injector will be used as the ATLAS injector for about half of the operating time in 1989.

The resonators, cryostat, and other components for the Phase II injector will be completed during the first half of 1989. As soon as these are available, assembly of the Phase II linac will start. The assembly will be completed by late 1989, and on-line installation and testing will start.

These activities will require an interruption of about three months in the operation of the Phase I injector, and the tandem will be needed again as an injector during this period.

Fabrication of the components (resonators and cryostat) needed to complete the last phase of the positive-ion injector (Phase III) will be started as soon as funding is available in 1989. Our objective will be to complete the work and start accelerating uranium beams before the end of 1990.

E. Proposal for a New Activity in Basic RF Superconductivity

In 1988 we propose to initiate a new activity consisting of investigations of basic properties of RF superconductivity. These investigations will be clearly independent of the short-term needs of any particular accelerator but are expected to have a significant impact on long-term progress in the application of RF superconductivity to many accelerators.

Examples of high-priority topics for study are (a) the maximum achievable surface magnetic field, (b) the effects of adsorbed gas on electron loading, and (c) factors that limit the maximum surface electric field. These and other studies will be carried out with a test resonator that can be easily modified to emphasize the influence of particular effects.

V. ACCELERATOR OPERATIONS

Introduction

This section is concerned with the operation of both ATLAS and the Dynamitron, two accelerators that are used for entirely different research. Developmental activities associated with the tandem injector of ATLAS and with the Dynamitron are also treated here, but developmental activities associated with the superconducting linac of the ATLAS system are covered separately in Sec. IV, because this work is a program of technology development in its own right.

A. OPERATION OF ATLAS

The Argonne Tandem-Linac Accelerator System (ATLAS) is operated as a source of energetic heavy-ion projectiles for use in nuclear-physics research and occasionally in other areas of science. The accelerator now consists of a 9-MV tandem electrostatic accelerator followed by a 40-MV superconducting linac. As shown by Fig. IV-1 of the preceding section, the linac has two major parts, the original prototype "booster" that has been in operation since 1978 and the ATLAS addition completed in September 1985. Beams can be directed either to the experimental apparatus in Area II or, with greater energy, to the newly installed apparatus in Area III. This arrangement contributes considerably to operational flexibility and efficiency.

Some aspects of the technology of the ATLAS linac are discussed in Sec. IV.

1. Summary of Operations

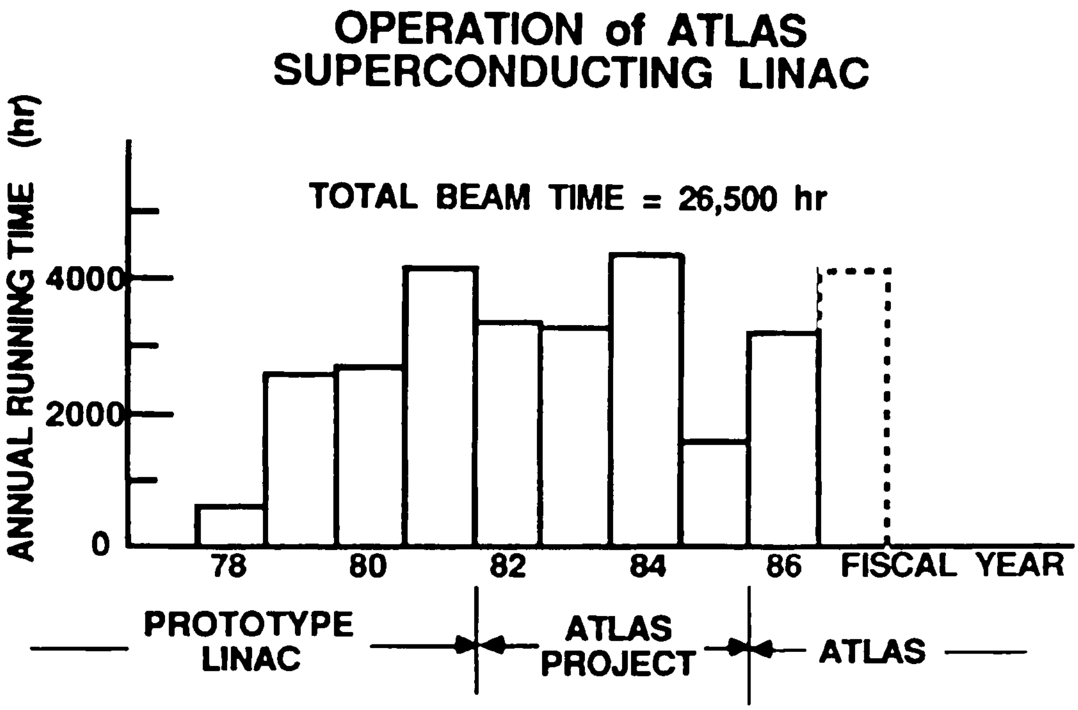
(P. K. Den Hartog, S. L. Craig, R. E. Harden, D. V. Hulet, F. H. Munson, Jr., and G. P. Zinkann)

Some operating statistics of ATLAS are summarized in Table V-I and Fig. V-1. The lower part of Fig. V-1 shows the frequency distributions of beams accelerated recently by ATLAS. The principal message in this distribution is that projectiles heavier than nickel are now being used frequently.

Table V-I. Operating Statistics for ATLAS

	Fiscal Year 1986	Fiscal Year 1987*
Distribution of Machine Time (hr)		
Research	2802	3750
Tuning	693	800
Machine Studies	369	400
Unscheduled maintenance	740	500
Scheduled shutdown	4156	3310
Total (1 yr)	8760	8760
Distribution of Research Time (%)		
ANL Staff	61	50
Universities (U.S.A.)	31	41
DOE National Laboratories	1	2
Other Institutions	7	7
Total	100	100
Outside Institutions Represented		
Universities (U.S.A.)	15	18
DOE National Laboratories	2	2
Other	7	8

*Projections based on experience through March 31, 1987.



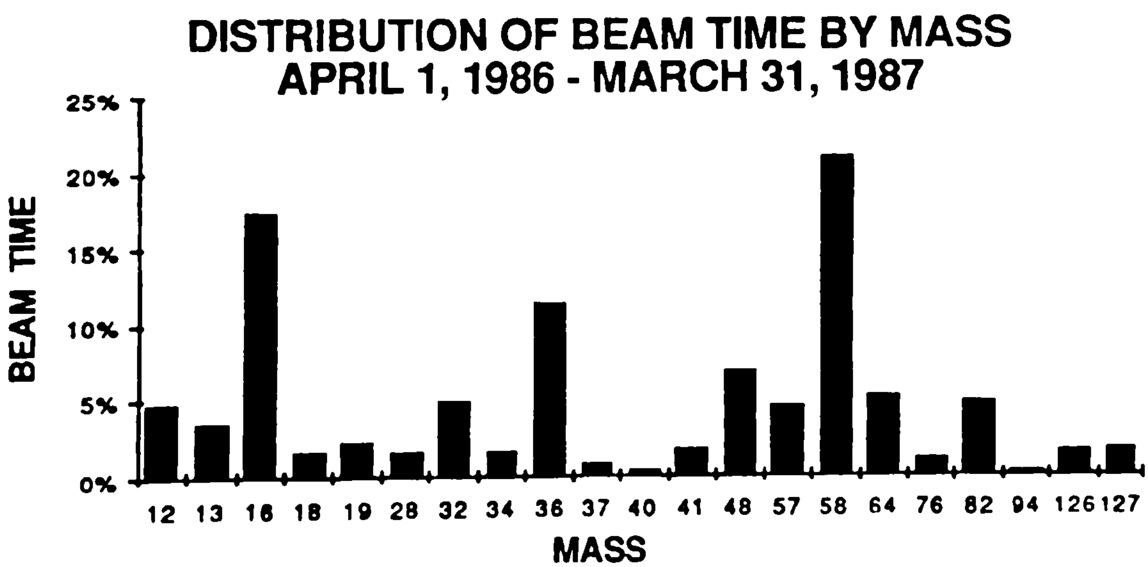


Fig. V-1. The upper histogram summarizes all running time on the ATLAS superconducting linac. The dip in running time in FY 1985 is associated with the completion and commissioning of ATLAS. The lower histogram shows the ion beams accelerated during 1986.

During 1986, the first year of operation of the full ATLAS system, the accelerator was operated on a regular schedule of 5 1/2 days of running time per week. In addition to this scheduled time, during the first half of the year (until budget cuts occurred), the operation was often extended through the weekend if needed to make up for unscheduled down time during the week. This mode of operation has proved to be quite effective in allowing users to complete planned research. Several reductions in support of the Heavy-Ion Program during the year made it impractical to enlarge the ATLAS operating staff during 1986, and consequently the scheduled running time was not extended to 6 days weekly, as had been planned. Under the present financial plan for FY 1987, it will be necessary to continue to restrict the operation of ATLAS to the same weekly schedule as in FY 1986.

The operation of ATLAS was interrupted in 1986 by two periods of scheduled down time required to make technical improvements. One of these improvements, the installation of an external contamination trap on a helium refrigerator and a modification of a helium distribution line, led to unexpected thermo-acoustical oscillations in the linac, and it took several weeks to track down and eliminate this subtle problem. In addition, various new auxiliary components (such as pulsers for the VCX fast tuners) failed at an alarming rate until the weaker elements were eliminated. In spite of such difficulties, however, ATLAS ran remarkably well during its first year of operation.

Looking toward the future, we foresee almost no need for long periods of down time until late 1988. The only such interruption planned for 1987 is the installation of a third refrigerator in September 1987, which may disturb the accelerator system for about three weeks.

The efficiency and quality of ATLAS operation will begin to be improved significantly in late 1987 by the completion of the extra linac section that has been under construction since 1985. This extra section, whose operation will be perfected off line, is to be used routinely as a quick replacement for on-line units that need maintenance. We expect in this way to gradually upgrade the performance of all parts of the linac with only minimal interruption of the operating schedule.

2. Status of ATLAS

ATLAS is a complete accelerator that is being operated routinely and effectively for research. Nevertheless, to the extent that the operating schedule permits, many parts of the accelerator are being steadily improved.

A shortage of helium refrigeration capacity continues to be a limitation on the usable accelerating field of the ATLAS linac. This problem will be eliminated or at least moderated in September 1987 when a third helium refrigerator is installed. This refrigerator will also cool the Phase I injector linac when it comes on line in late 1988.

During the initial operation of the full ATLAS system, there was some difficulty in controlling the operation of two connected refrigerators that serve somewhat different functions. This control problem has now been solved by the design and installation of a control system that has removed the need for a human operator most of the time. This good experience makes us confident that the third refrigerator can be connected to the cooling system without much difficulty.

During 1986, the operating characteristics of each on-line resonator was carefully studied by measuring its Q as a function of accelerating field. In a number of units, the Q was found to be much smaller than had been expected on the basis of off-line tests. This low-Q behavior led to the identification of several classes of component failure. The most serious of these is the breakage, caused by thermal cycling, of the thin niobium material in the neighborhood of ports for RF power input and phase control. This problem has been fixed, and hopefully eliminated, by modifying the mechanical design of the ports. However, some units that have not yet experienced this kind of failure are expected to do so in the future, since some of the failed units had been in operation for about seven years.

Other problems identified by the Q measurements were component failures and design flaws in the RF input and output probes and in the VCX fast tuner. Design changes have greatly reduced the power losses in the input and output probes. However, the upgrading of the fast tuner is a more difficult problem that requires some off-line developmental effort. This work is now in progress.

The liquid-nitrogen-control system associated with the original booster linac has been upgraded to the standard of the newer ATLAS linac during the past year. This improvement has reduced equipment failure and resulted in a noticeable reduction in liquid-nitrogen usage.

There is a continuing effort to develop and perfect the computer-based system that controls ATLAS and its beam lines. One feature of special interest is a program that routinely monitors the operating phase of each resonator. This program has detected changes in phase that occasionally cause a change in the operating energy, a phenomenon that was previously unexplained. The mechanism for this infrequent effect is still being investigated.

Several improvements of major beam-line components mentioned in earlier reports have proven to be effective during the past year. Moving the beam chopper further upstream, where it functions as velocity selector, has largely eliminated the problem of analyzing the spectra of doubly-stripped ion beams from the tandem.

The RF deflector installed in front of the linac is proving to be a very effective way to eliminate unwanted beam pulses. This capability is extensively used by experimenters to lengthen the time between pulses and to generate non-standard pulse patterns.

The time-of-flight energy-measurement system continues to be improved and is now generally accepted as the primary source of information about the beam energy. The beam energy is now measured with an absolute accuracy of about 5 parts in 10^4.

Other than essential maintenance, most of the work on the tandem has been devoted to the injection system during the past year. Special effort has been expended on the high-voltage power supplies of the voltage platforms. Large improvements appear to have been made by modifying the design of these major commerical devices, but the effectiveness of these improvements has not yet been tested by long operational experience.

3. Long-term Improvements in Progress

Beam Pulsing

We are continuing to try to improve all aspects of beam-pulsing technology. This is requiring a step-by-step refinement of all parts of the accelerator: ion-source operation, low-energy beam bunching, linac tuning, rebuncher performance, diagnostic techniques, and all parts of linac control that influence operational stability. The technical improvements and understanding resulting from this effort are benefical, of course, for all aspects of accelerator operation.

Steady progress is being made in the quality of pulsed beams delivered to users. The narrowest pulses obtained now are 120 ps for ^{16}O and 150 ps for ^{58}Ni beams. This level of bunching is turning out to be extremely valuable in a variety of fast-timing measurements.

Parasitic Beams

ATLAS users, and especially outside users, have shown a keen interest in the development of a parasitic-beam capability at ATLAS. Consequently, the needs of users and the technical possibilities are being systematically studied. We conclude that what is needed and what is technically possible is a system of parasitic beams designed to provide a wide variety of capabilities. Ideally, such a system might include (a) several special-purpose facilities with low-intensity CW beams, (b) a facility for detector development, (c) sharing of beam between Areas II and III, and (d) micropulse-by-micropulse deflection of the beam into several of the widely-used beam lines in Area III.

A system such as is outlined above has not been practical heretofore because (a) the beams available from the tandem are too weak and (b) some of the required technology has not existed. However, the positive-ion injector for ATLAS will remove both of these obstacles: the available beam intensity will be more than can be used in most experiments and the class of superconducting resonators being developed for the injector linac could (with a modest change in design) serve as a beam deflector with exceptional capabilities. Based on these major advances, an attractive conceptual design of a pulse-by-pulse beam separator has been developed.

The study of the concept of a system of parasitic beams is still in progress, with continuing discussions of user needs and investigations of technical questions. Tentatively, our plan is to develop one or two inexpensive parasitic-beam capabilities during 1987 and 1988 and, simultaneously, to prepare a proposal for a comprehensive parasitic-beam system to be built with FY 1990 funding.

4. Plans for 1988

During most of 1988, ATLAS will continue to be operated continuously for research, with no significant interruption now foreseen. At the level of support in the President's Budget for FY 1988, we will have to continue to limit the operating schedule to 5 1/2 days per week.

Throughout 1988, the spare accelerator section completed in 1987 will be interchanged from time to time with an on-line unit in need of maintenance. In this way, about half of all sections will be brought up to a high standard of performance each year. This capability of interchanging functioning sections is important not only because it permits malfunctions to be corrected but also because it will permit all parts of the technology to be gradually upgraded without a significant loss of running time.

The study of beam bunching will continue throughout 1988, since narrow-bunching capability is so important to ATLAS users. As is true now, this future work will involve attempts to acquire a more complete understanding of all parts of the accelerator system.

The development of parasitic-beam capability at ATLAS will continue in 1988. This work will include (a) experimental use of low-frequency beam switching between Area II and III, (b) installation of a special-purpose parasitic facility that provides a low-intensity CW beam, and (c) the preparation of a proposal for a comprehensive system of parasitic beams for ATLAS.

The operation of ATLAS in its present form, with the tandem serving as an injector, will continue until late 1988. By then, the Phase I positive-ion injector will be operational and partially tested. Assuming that no major unexpected problems are encountered, the new injector will be coupled to ATLAS and used for research as soon as the injector has been adequately tested.

Based on our earlier experience, we are optimistic that the change from the tandem to the linac injector will cause very little loss of running time. Also, we expect that it will immediately provide major benefits in terms of more intense beams for the research program.

When the tandem is not serving as an injector of ATLAS, the Environmental Research Division of the Laboratory plans to use it as a tool for accelerator mass spectroscopy. However, the Physics Division will continue to have control of and access to the tandem until at least FY 1990, when the Phase II linac will be functional.

5. Plans for 1989

All of the long-term accelerator-improvement activities planned for 1988 will extend into 1989. In particular, the development of parasitic beams will be carried out with increasing vigor, and users are expected to find such beams to be increasingly valuable. The most important change planned for 1989 is the installation of the 8-MV Phase II injector linac. This will extend the mass range available from ATLAS up to about A = 200 and will improve performance to an important extent for all lighter ions. During the 3-month period when the enlarged injector linac is being installed, the operation of ATLAS will be continued by using the tandem again as an injector.

6. Assistance to Outside Users of ATLAS

During the past year, substantial progress has been made in providing organized assistance to outside users of ATLAS. There are 150 outside members of the User Group from 49 institutions and outside users were involved in 2/3 of all experiments performed in 1986. The user-assistance program fills an essential function.

A user liaison physicist continues to play a key role in channeling assistance to outside users. The major components of his responsibility are: (1) to provide the needed information and organizational assistance to committees, workshops, and other meetings involving outside users; (2) to provide instruction in the use of and technical information about ATLAS and its experimental systems to users; (3) to assist outside users in all aspects of initiating and planning an experiment; (4) to the extent that is appropriate and feasible, to assist users in the actual performance of experiments; (5) to provide instruction and help with the use of computer hardware and software; (6) to instruct the users in the safety procedures to be followed when using the ATLAS facility; (7) to assist in the operation of the technical support group; and (8) provide an interface between the user and the technical support and ATLAS operation groups.

The Program Advisory Committee (PAC) for ATLAS (having five members from other institutions and two from Argonne) continues to meet regularly during the year. In 1987 PAC meetings were held on March 8 and October 4 to recommend experiments for running time at ATLAS. In accordance with PAC policy, three members were rotated off the committee. Douglas Cline (University of Rochester), Luciano Moretto (Lawrence Berkeley Laboratory) and Teng Lek Khoo (ANL) have replaced Walter Benenson (Michigan State University), Richard Diamond (Lawrence Berkeley Laboratory) and Walter Henning (ANL). In addition, C. Lewis Cocke (Kansas State University) was added to the PAC to provide a more complete review of atomic physics proposals. On the average, the PAC is asked to review 30 proposals for 130 days of running time per meeting. The running time requested in these proposals continues to stay at the level of approximately twice the number of days available for experiments.

The Executive Committee of the Organization of ATLAS Users held two meetings in 1986. The annual User Group meeting was held during the April APS meeting in Washington, D.C.; the combined Workshop/"Open PAC" meeting held on October 2 and 3 at ANL was attended by about 80 scientists. The purpose of these meetings was to discuss progress at ATLAS, and future plans for the accelerator and the experimental facilities. The Open PAC meeting was held to give the PAC members a better understanding of the ongoing programs at ATLAS. In accordance with the Executive Committee Charter a new committee was elected by the user community this past year. The new members are Charles Maguire (Vanderbilt University) and Udo Schroeder (University of Rochester). Thomas Cormier (University of Rochester), as ex-chairman, will serve a second two-year term. James Kolata (University of Notre Dame) was reelected and chosen to be (by the other Committee members) the new committee chairman. Frederick Becchetti (University of Michigan) was on the previous Executive Committee.

The magnitude of the outside use of the accelerator during the past year has been increasing. The following two lists give (1) the experiments performed by outside users and (2) the institutions represented. As may be seen from the names associated with each experiment, university groups are playing a major role in an important fraction of the experiments and a dominant role in some.

a. Experiments Involving Outside Users

All experiments in which outside users participated during calendar year 1986 are listed below. The spokesperson for each experiment is given in square brackets after the title. The names in parentheses are Argonne collaborators.

(1) Nuclear Structure at Very High Spin on the Yrast Line and in Its Vicinity in the ^{147}Gd Nucleus [Janssens]
M. Drigert, U. Garg, University of Notre Dame; P. Daly, M. Piiparinen, M. Quader, Z. Grabowski, W. Trzaska, Purdue University; H. Emling, GSI; (T. L. Khoo, R.V.F. Janssens, I. Ahmad, B. Dichter)

(2) Resonant Transfer and Excitation for Highly-charged Iron Ions [Tanis]
J. Tanis, M. Clark, Western Michigan University; W. Graham, University of Ulster; K. Berkner, Lawrence Berkeley Laboratory; D. Schneider, Hahn-Meitner Institute; G. Bernstein, University of Toledo; (E. Kanter)

(3) Energy and Target Dependence of Incomplete Fusion Processes in ^{28}Si-induced Reactions [Vineyard]
G. Stephans, MIT; F. Prosser, V. Reinert, University of Kansas, C. Maguire, Vanderbilt University; (M. Vineyard, D. Kovar, B. Wilkins, D. Henderson, C. Beck, C. Davids)

(4) Radiation Chemistry Studies with Heavy Ions [LaVerne]
J. A. LaVerne, R. Schuler, R. Steinback, University of Notre Dame

(5) Accelerator Mass Spectrometry of ^{41}Ca [Henning]
M. Paul, Hebrew University; (W. Henning, B. Glagola, Z. Liu, E. Rehm, W. Kutschera, J. Yntema)

(6) Electromagnetic Transitions in Neutron-rich Nuclei in the A = 40 Region [Kozub]
R. Kozub, J. Shriner, Tennessee Technological University; M. Drigert, University of Notre Dame; (R. Holzmann, R. Janssens, T. Khoo)

(7) (a) Evolution of the γ-ray Continuum as a Function of Neutron Number in Dysprosium Isotopes; (b) Lifetimes of Very High Spin States in ^{156}Dy [Holzmann]
M. Drigert, U. Garg, University of Notre Dame; H. Emling, GSI; (R. Holzmann, I. Ahmad, B. Dichter, R. Janssens, T. Khoo, W. Ma)

(8) Accelerator Mass Spectrometry of ^{41}Ca [Henning]
M. Paul, Hebrew University; (W. Henning, P. Billquist, B. Glagola, W. Kutschera, Z. Liu, E. Rehm, J. Yntema)

(9) Radiation Chemistry Studies with Heavy Ions [LaVerne]
J. LaVerne, R. Schuler, University of Notre Dame

(10) Quasielastic Reactions of ^{28}Si with ^{208}Pb [Kolata]
J. Kolata, R. Vojtech, University of Notre Dame; (D. Kovar, E. Rehm)

(11) Evaporation Residue Cross Section Behaviour for ^{16}O + ^{40}Ca at E > 10 MeV/u [Kovar]
C. Maguire, Vanderbilt University; F. Prosser, University of Kansas; (D. Kovar, S. Sanders, R. Janssens, B. Wilkins, C. Beck, M. Vineyard, W. Ma, D. Henderson, T. Wang, T. Moog)

(12) Gamma Decays in Fission Fragments (i) Spectroscopy of Neutron-rich Nuclei, (ii) Primary Fragment Shapes [Phillips]
M. Drigert, University of Notre Dame; J. Durell, W. Gelletly, W. Phillips, University of Manchester; (R. Janssens, I. Ahmad, R. Holzmann)

(13) Incomplete Fusion Reactions Induced by ^{12}C at 10-15 MeV/u [Tserruya]
I. Tserruya, P. Jacobs, Weizmann Institute; C. Maguire, Vanderbilt University; F. Prosser, University of Kansas; (D. Kovar, B. Glagola, B. Wilkins, C. Beck, T. Wang, D. Henderson)

(14) Light-particle Light-particle Coincidence Measurements at E > 10 MeV/u [DeYoung]
P. DeYoung, D. Robins, Hope College; J. Alexander, G. Gilfoyle, G. Auger, SUNY at Stony Brook; (D. Kovar, C. Beck, B. Glagola)

(15) Search for Shape Isomers in ^{56}Ni [Dichter]
M. Drigert, University of Notre Dame; W. Kühn, Giessen; (B. Dichter, S. Sanders, R. Janssens, R. Holzmann, T. Wang)

(16) Mass Measurements of Very Neutron-rich Nuclei using ^{18}O-induced Reactions and a Superconducting Solenoid [Stern]
R. Stern, F. Becchetti, J. Janecke, M. Dowell, University of Michigan; W. Phillips, University of Manchester; (D. Kovar, C. Beck)

(17) Study of the Tilting-mode Relaxation in the Heavy-ion-induced Fission Reaction ^{165}Ho + ^{58}Ni at 7.0 and 10.0 MeV per Nucleon [Toke]
J. Toke, U. Schroeder, I. Govil, J. Wile, W. Zank, University of Rochester; (E. Rehm)

(18) The Symmetric Fusion Reaction $^{82}Se + ^{82}Se - ^{166}Er^{*}$; Is Neutron Evaporation Suppressed [Daly]
P. Daly, M. Piiparinen, M. Quader, Purdue University; M. Drigert, University of Notre Dame; W. Kühn, Universitat Giessen; (T.L. Khoo, W. Ma, R. Holzmann)

(19) Test of New NaI Light-ion Detectors [Davids]
C. Maguire, Vanderbilt University; F. Prosser, University of Kansas; (C. Davids, D. Kovar, C. Beck)

(20) Doppler-free Auger Electron Spectroscopy from Ne-like High-Z Atoms [Schneider]
D. Schneider, L. Curtis, R. Schectman, University of Toledo; K. Berkner, Lawrence Berkeley Laboratory; (E. Kanter, G. Berry)

(21) Resonant Transfer and Excitation for Highly-charged Iron Ions [Tanis]
J. Tanis, M. Clark, W. Graham, Western Michigan University; (Kanter)

(22) Heavy-ion-induced Desorption of Organic Molecules (cont.) [LaVerne]
J. LaVerne, R. Schuler, R. Steinback, University of Notre Dame

(23) Origin of Neutron Suppression in Fusion of Heavy Ions; Spectra of (i) the Low-energy Neutrons, (ii) Excess Gamma-ray Energy [Kolata]
J. Kolata, L. Gossing, M. Drigert, University of Notre Dame; W. Kühn, University of Giessen; M. Quader, Purdue University; R. M. Ronnigen, Michigan State University; (T. L. Khoo, R. V. F. Janssens, R. Holzmann, B. Dichter, W. C. Ma)

(24) Charged-particle Gamma-ray Coincidences as a Probe of Nuclear Structure at High Spin [Betts]
W. Kühn, University of Giessen; M. Drigert, University of Notre Dame; (R. R. Betts, R. V. F. Janssens, S. J. Sanders, R. Holzmann, B. Dichter, W. C. Ma, T. L. Khoo)

(25) Electromagnetic Transitions in Neutron-rich Nuclei in the A = 40 Region via Reactions of ^{36}S with ^{9}Be [Kozub]
R. Kozub, J. Shriner, M. Hindi, R. Moyers, R. Bybee, Tennessee Technological University; J. Kolata, M. Drigert, University of Notre Dame; (R. Janssens, R. Holzmann, T. Khoo, W. Ma, I. Ahmad)

b. Outside Users of ATLAS and of ATLAS Technology During the Period January 1986 - January 1987

(1) Hope College
P. DeYoung
D. Robins

(2) Purdue University
P. J. Daly
Z. W. Grabowski
M. Piiparinen
M. Quader
W. H. Trzaska

(3) SUNY, Stony Brook
J. Alexander
J. Gilfoyle
G. Auger

(4) University of Kansas
F. W. Prosser
V. Reinert

(5) University of Michigan
F. Becchetti
M. Dowell
J. Janecke
W. Liu
S. Shaheen
R. Stern

(6) University of Notre Dame
U. Garg
J. Kolata
M. Drigert
L. Goettig
R. Vojtech
J. A. LaVerne
R. H. Schuler
R. T. Steinback

(7) University of Toledo
L. Curtis
R. Schectman

(8) Hahn-Meitner Institute
D. Schneider

(9) Massachussetts Institute of Technology
G. Stephans

(10) Hebrew University
M. Paul

(11) Tennessee Technological University
R. Kozub
J. Shriner
M. Hindi
R. Moyers
R. Bybee

(12) University of Manchester
J. Durell
W. Gelletly
W. Phillips

(13) University of Giessen
W. Kühn

(14) Vanderbilt University
C. F. Maguire

(15) Weizmann Institute
I. Tserruya
P. Jacobs

(16) Western Michigan University
E. M. Bernstein
M. W. Clark
J. A. Tanis

(17) University of Ulster
W. Graham

(18) University of Rochester
J. Toke
U. Schroeder
I. Govil
J. Wile
W. Zank

(19) Florida State University
J. Fox
A. Frawley

(20) Kansas State University
T. Gray
K. Karnes
V. Needham

(21) Lawrence Berkeley Laboratory
K. Berkner

(22) Michigan State University
R. Ronnigen

(23) GSI
H. Emling

c. Summaries of the User Programs, January 1986 to January 1987

c.i. The University of Notre Dame

1. Nuclear Physics (U. Garg, M. Drigert, E. Funk, J. Kolata, J. Mihelich, and R. Vojtech)

A group from the University of Notre Dame is playing an important role in developing the research program at ATLAS. One of their main interests is the study of the behavior of nuclei at high spin in the Pt-Os-Ir region, with emphasis on the origins of the backbending phenomenon in these nuclei, and measurements of the lifetimes of high-spin yrast states. This group has also participated in most of the experiments performed with the new BGO gamma-ray facility. One of their collaborators (Dr. M. Drigert) has been based at Argonne since the summer of 1986 in order to render the collaboration more effective.

Another project concerns the study of incomplete fusion, quasielastic reactions and the emission of light particles. In the past year one study of the $^{28}Si + ^{208}Pb$ system was undertaken. It is planned to extend this study to higher energies in the future.

A major activity of this past year was the continuation of the second phase in the construction of a gamma-ray facility consisting of a BGO sum-multiplicity array of 50 elements combined with 12 Compton-suppressed germanium detectors. In this project, the Notre Dame group is responsible for the array. This task consists of assembling and testing the BGO detectors and developing the electronic read-out system. This construction project will be completed in 1987.

2. Atomic Physics (A. E. Livingston, E. J. Galvez, A. J. Mazure, A. D. Zacarias)

Measurements are being made of the fine structure in helium-like titanium and nickel. The excited beams are made in a beam foil and the radiation is analyzed using normal and grazing-incidence uv spectrometers. The titanium results from several ATLAS runs have yielded a measurement of the 2s - 2p (J = -2) transition. These results have been published. The recent work has been aimed at extending these measurements to helium-like nickel ions.

3. Radiation Chemistry (R. Schuler, J. LaVerne and R. Steinback)

In the last year, a Radiation Chemistry group has continued studies of the process of track formation, local density of radicals and other reactive intermediates formed in a heavy-ion track in water. The understanding of these processes is important because of increased usage of heavy ions in radiation biology and medical therapy. This program is an extension to higher energies of work begun at Notre Dame and ATLAS. In the last year experiments were performed using ^{11}B, ^{12}C and ^{16}O projectiles at booster-linac energies and ^{12}C at ATLAS energies. In the next year, these experiments will be extended to the full ATLAS energy for ^{16}O and ^{58}Ni.

c.ii. Purdue University (P. Daly, Z. Grabowski, J. McNeill, M. Piiparinen, M. Quader, and W. Trzaska)

The Purdue University group is working on high-spin nuclear states at ATLAS, with several thesis students. They use in-beam gamma-ray techniques directed at several aspects of nuclear structure at high spin, testing the validity of the $Z = 64$ sub-shell closure through spectroscopic studies of $N = 82$ nuclei close to the proton drip line. They have extended these studies in the last year by making use of the Compton-suppressed germanium detectors of the BGO facility.

The group is also building a superconducting solenoid lens to be used as a conversion-electron spectrometer. The solenoid is being constructed at Purdue and, after testing there, will be installed at Argonne on a beam line in Target Area II of ATLAS. Arrival at Argonne is anticipated in early 1987.

c.iii. Tennessee Technological University (R.L. Kozub, J.F. Schriner, M.M. Hindi, R. Moyers, and R. Bybee)

The group from Tennessee Technological University is interested in the structure of neutron-rich nuclei in the $A = 40$ region. These are studied at ATLAS using inverse reactions (such as $^{36}S + {}^{9}Be$) in experiments where gamma rays measured with the Argonne-Notre Dame BGO gamma-ray facility are detected in coincidence with charged particles (p, d, ^{3}HE, alpha...). In order to perform these experiments they have built a small chamber holding two DE-E telescopes which, nevertheless, fits inside the space available in the

BGO array. This chamber has proven to be very useful for several other experiments performed at the laboratory.

c.iv. University of Kansas and Vanderbilt University Collaboration (C. F. Maguire, A. V. Ramayya, F. W. Prosser, and V. Reinert)

The program for the development of the techniques for the use of NaI(Tl) detectors as light charged-particle detectors was continued during the last year in collaboration with the ANL group. Using pulse-shape discrimination and time of flight, the mass and charge of light particles ($A < 6$) can be determined. The techniques and calibrations have progressed to the point that these detectors [15 NaI(Tl) crystals] have been used in several experiments now. Work continues on the improvement of the techniques and the development of electronics to handle large arrays of these detectors. The program of study of the energy and projectile dependence of fusion and incomplete fusion processes for light- and medium-weight heavy-ion systems has also continued with participation in several experiments during the last year. Major emphasis has been on the coincidence experiments where the NaI(Tl) detectors have been used.

c.v. University of Michigan (F. Becchetti, J. Janecke, R. Stern, M. Dowell, S. Shaheen, W. Liu, and P. Schulman)

During this year the superconducting solenoid, which had been developed over the last two years, was successfully used to take data. Beams of ^{18}O were used to measure the charge, mass and low-lying levels of neutron-rich light nuclei (e.g., ^{24}Ne). The development program and the data obtained constitute a Ph.D. thesis project for R. Stern. Measurements were also performed to study the very high-energy light particles produced in heavy-ion reactions. In reactions induced by heavy ions such as ^{32}S, and ^{58}Ni at bombarding energies $E_{lab} > 10$ MeV/nucleon, alpha-particle energy spectra extending to nearly the full bombarding energy and proton spectra extending to about the bombarding energy were observed. The mechanism responsible for these light particles whose velocities are several times the velocity of the projectile cannot be easily understood, and the results are presently being submitted for publication.

c.vi. University of Toledo (D. Schneider, L. Curtis, and R. Schectman)

A series of measurements is in progress to study the level structures of high-Z Ne-like and Na-like ions. In 1986, a beam of excited Ne-like Ni^{18+} ions was produced in ion-atom collisions with a gas target and used to study LMM Auger emission. In the experiment, the Auger electrons ejected from the excited projectile ions were analyzed by an electron spectrometer at zero degrees with sufficient resolution to resolve individual Auger lines. The experiment is a test of fundamental atomic structure theory and of models regarding the dynamic excitation processes in highly-ionized multi-electron systems.

c.vii. Western Michigan University and Lawrence Berkeley Laboratory Collaboration (J. Tanis, M. Clark, W. Graham, E. Bernstein, and K. Berkner)

This group has begun a series of atomic-physics studies at ATLAS to measure coincidences between X-rays and the outgoing projectile charge states in ion-atom collisions. The goal of this work is to probe fundamental atomic interactions in ion-atom collisions by correlating projectile charge-state changing events with X-ray emission. In the experiment, a range of energies was used to span the region of resonant transfer and excitation for high-energy Li-like nickel ions. This process is a close analog of dielectronic recombination which is of fundamental interest in plasma physics. The experiments carried out at ATLAS with fast Ni beams represent the heaviest system studied to date. There were two runs of this experiment in the past year. The first run, which took place in January, was set up in the large scattering chamber and involved electrostatic analysis of the charge states emerging from the target. In the second run, which took place in October, the magnetic spectrograph in Target Area III was used. Additional runs of the experiment will be required to complete the data for Ni.

c.viii. SUNY, Stony Brook and Hope College Collaboration (R. McGrath, J. Alexander, J. Gilfoyle, M. Gordon, P. DeYoung, M. Hammond, and K. Kossen)

This collaboration has undertaken measurements to understand the mechanisms of light-particle production in heavy-ion collisions. Experiments to measure inclusive spectra and coincidences between light particles were carried out in the new ATLAS 36" scattering chamber in the previous year and the data analysis has been progressing well. In the last year a major experimental run was mounted but was not completed because of problems with the accelerator. The detection system in these measurements consists of a seven-NaI(Tl)-detector array (developed at Stony Brook) and two back-angle dE-E Si telescopes. The system allows the measurement of energy, charge and mass of the detected particle. The coincidence measurements were carried out to study the relative momentum of particles emitted at small relative angles. This series of measurements is to be continued at ATLAS to study the role of the entrance channel, and the dependence on the bombarding energy.

c.ix. Weizmann Institute of Science, Rehovot (I. Tserruya and P. Jacobs)

In the previous year this collaboration carried out an experiment to measure the energy dependence of complete fusion and incomplete fusion for the reactions ^{12}C + ^{90}Zr, ^{120}Sn, ^{160}Gd, and ^{197}Au. The results have been analyzed showing evidence that incomplete fusion processes are present at low bombarding energies (starting not far above the Coulomb barrier). These results should soon be submitted for publication. In the last year a major coincidence study of the same reactions was mounted but not completed because of problems with the accelerator. These measurements are scheduled to be performed in the present year. The experiments are carried out by measuring the velocity spectrum of the reaction products with a single large-area Breskin counter at zero degrees. This detector measures in a single run 80% of the total yield of evaporation residues and uses time of flight to discriminate between complete and incomplete fusion.

d. ATLAS - Technology Transfer

In addition to providing assistance to outside users of the ATLAS beams, we are also providing assistance in the use of the ATLAS technology.

d.i. Florida State University (J. Fox and A. Frawley)

Argonne has fabricated the niobium resonators and some auxiliary devices required for the superconducting-linac energy booster being built at Florida State University. Under this arrangement, personnel from FSU have come to ANL to assemble and test the resonators. The resonator-fabrication work for FSU was completed during 1986.

d.ii. Kansas State University (T. Gray, K. Karnes, and V. Needham)

Argonne is fabricating the niobium resonators and some other linac components required for the superconducting decelerating linac being built at Kansas State University. Several staff members from KSU spent a substantial period of time at ANL during 1985 in order to learn the technology, and they have continued to return to assemble and test the resonators. In the future, some of the KSU resonators will be tested at KSU in their own beam-line cryostats.

B. OPERATION OF THE DYNAMITRON FACILITY

The Physics Division operates a high-current 5-MV Dynamitron accelerator which has unique capability as a source of ionized beams of most atoms and many molecules. A layout of the facility is shown in Fig. V-2. Among the experimental facilities associated with the Dynamitron are (1) a beam line capable of providing "supercollimated" ion beams permitting angular measurements to accuracies of 0.005 degree, (2) a beam-foil measurement system capable of measuring lifetimes down to a few tenths of a nanosecond, (3) a set-up for testing a polarized deuterium target for use in high-energy storage rings, (4) a variety of experimental apparatuses for weak-interaction studies, (5) a laser/ion-beam interaction beam line where laser beams from an argon pump and a dye laser are available coaxially and simultaneously with the Dynamitron ion beam, (6) a post-acceleration chopper system giving beam pulses of variable width from about one nanosecond to the millisecond range at repetition rates variable up to 8 MHz, (7) a scattering chamber for electron spectroscopy with electrostatic parallel-plate electron spectrometers with variable energy resolution (0.1% to 5%) and the capability to measure electron energies up to a few keV as a function of observation angle, and (8) two general-purpose beam lines used for a variety of short-term experiments. A VAX-11/750 computer system is available for on-line data analysis and for the control of experiments.

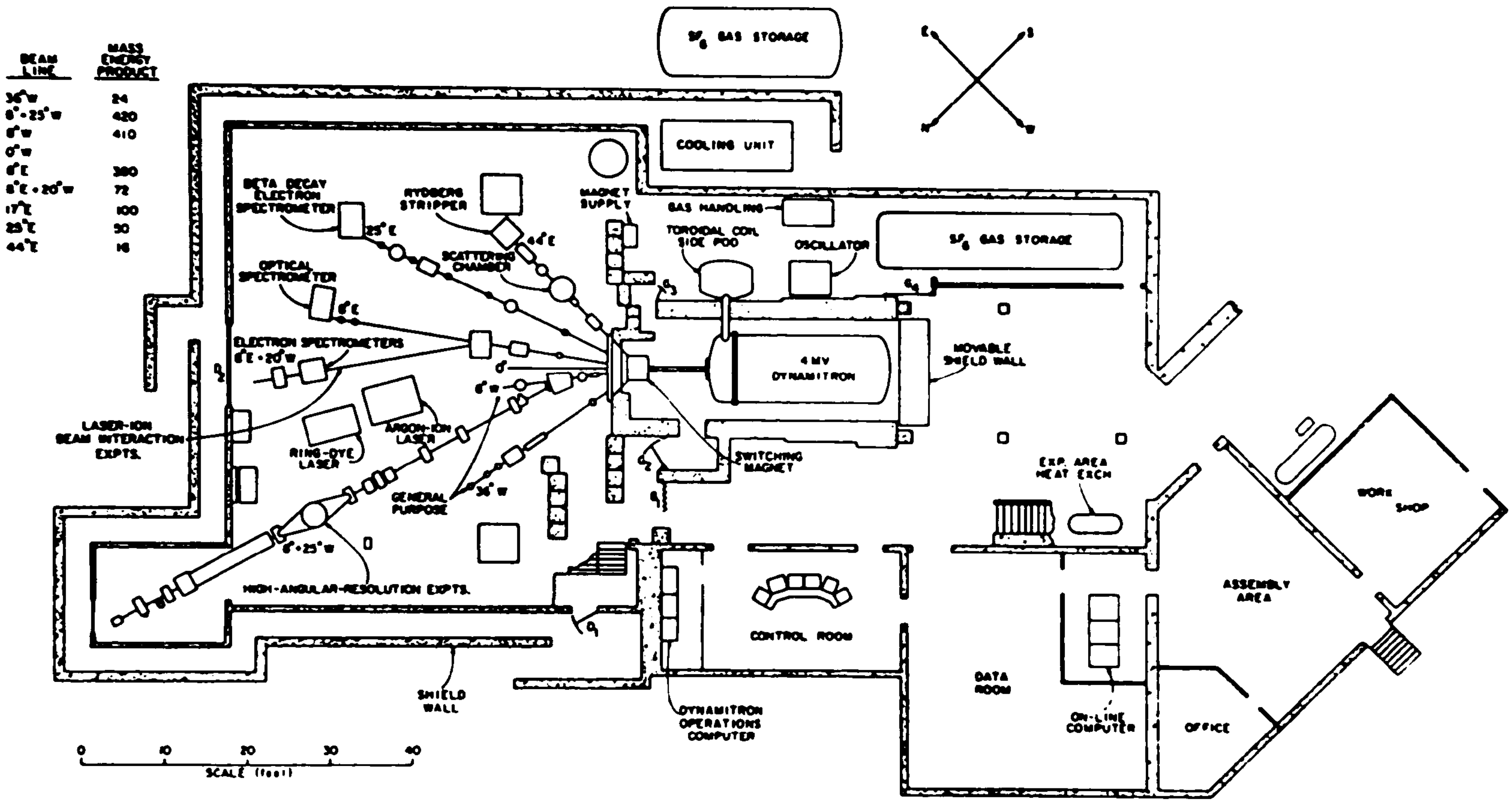


Fig. V-2. Layout of the Dynamitron Accelerator Facility.

1. Future Developments at the Dynamitron

(R. L. Amrein, H. G. Berry, E. P. Kanter, A. E. Ruthenberg, and B. J. Zabransky)

The Dynamitron is expected to continue to be used primarily by the accelerator-based atomic physics programs in the Physics Division. These include the work with fast molecular-ion beams and the atomic structure programs. Most of the planned developments are aimed at addressing specific problems for these research programs.

The studies of molecular-ion structures require new ion sources to prepare molecules in well-defined initial states. We have investigated various schemes appropriate for sources of state-selected molecular ions in the Dynamitron high-voltage terminal. Several experiments have been carried out this past year with molecular-ion beams produced by low-energy electron impact in the terminal. For example, for experiments on CH_4^+, such a source was constructed by modification of the electrode structure of a conventional duoplasmatron ion source. Several other schemes are under consideration for producing vibrationally cold molecular ions.

Work has also begun on a photoionization source to select higher-lying vibrational excitations. This, and other sources under consideration, will present large gas loads to the accelerator tube and this necessitates the installation of a terminal pumping system. Such a system is currently under design and we hope to have it functional early in 1988. Further developments will also be required to instrument the terminal region to control the new source.

Our efforts to improve the voltage stabilization of the terminal will continue. The recent change of the fans that recirculate the SF_6 insulating gas has removed the last of the low-frequency sources of voltage fluctuation. A new generating voltmeter is being constructed this year which will allow us to study the much weaker high-frequency components of the ripple. This effort should make it feasible to perform several collinear laser/fast beam experiments planned for the atomic structure program.

We also plan to pursue new sources of multicharged ions. A Physicon ion source has been obtained for this purpose. When our new ion-source test-bench facility is completed, we plan to investigate the coupling of this new source to the accelerator tube to optimize beam currents and beam-velocity profiles. We hope to use this source to provide some multi-charged ion beams and possibly beams with high metastable-state populations.

2. Operational Experience of the Dynamitron

(B. J. Zabransky, R. L. Amrein, and A. E. Ruthenberg)

Overall, the Dynamitron continued to perform well during the past year. It was shut down for a total of approximately 6 months spread over the year. During this time, the technical staff assisted in the construction of beam lines, small accelerators, ion sources, and machine modifications. The Dynamitron is now usually staffed 8 hours a day by two full-time staff, but can also be operated by experienced scientific personnel. This arrangement has proved to be effective. If the experiment requires it, the Dynamitron can continue to run through the night, manned only by the experimenters, or upon request, the Dynamitron can be staffed for two shifts a day. This is normally done with outside users or others not familiar with the operation of the accelerator.

During the year the accelerator was operated a total of 2157 hours. Of this time 1479 hours (69%) were scheduled for experimental research during which a beam was provided to the experimenters 75% of the time. Machine preparation time used up 17% of the scheduled research time and machine malfunctions 8%. Scheduled accelerator improvements (including the upgrading program) and modifications used a total of 678 hours or 31% of the total available time.

The great versatility of the Dynamitron continued to be exploited by the research staff. Ion currents on target varied from 1×10^{-7} amperes to 200 microamperes with ion energies ranging from 0.4 to 4.8 MeV. A wide range of both atomic and molecular ions was delivered on target. They include: $^{1}H^{+}$, $^{1}H_2^{+}$, $^{2}H^{+}$, $^{3}He^{+}$, $^{4}He^{+}$, $^{12}C^{+}$, $^{12}CH^{+}$, $^{14}N^{+}$, $^{15}N^{+}$, $^{12}CH_2^{+}$, $^{16}O^{+}$, $^{12}CH_4^{+}$, $^{16}OH_2^{+}$, $^{20}Ne^{+}$, $^{20}Ne^{++}$, $^{12}C_2H_3^{+}$, $^{12}C_3^{+}$, $^{12}C_3H^{+}$, $^{12}C_3H_3^{+}$, $^{12}C_3H_3^{++}$, $^{12}C_3H_4^{+}$, $^{14}N^{15}N^{++}$, $^{32}SH_2^{+}$, $^{40}Ar^{+}$, and $^{84}Kr^{+}$.

A total of 41 investigators used the Dynamitron during 1986 in some phase of their experimental research. Of these, 19 were from the Physics Division, 10 were outside users from other research facilities, one was a member of the Resident Graduate Student Program. In addition, 7 graduate students, one undergraduate student, and one pre-college student participated in research at the Dynamitron. Of the scheduled time, 78% went to experiments involving members of the Physics Division and 12% was exclusively assigned to non-Argonne users. However, outside users collaborated in experiments that used 32% of the total available time. Graduate students, undergraduate students, pre-college students, and participants in the Resident Graduate Student Program worked on experiments that used 27% of the time.

Maintenance problems on the Dynamitron itself have been very minor. Some of the support equipment had many problems. Two recirculating pumps had to be changed. One for the cooling of the Dynamitron and one for the cooling of the experimental area. We also had problems with two outside air-conditioning units. One cools the Dynamitron data room and VAX-11/750 computer and the other cools the Dynamitron itself. We have replaced both of these units with heat exchangers that operate using the building chilled water. This new system has proved to be very reliable and extremely effective.

One of the three SF_6 gas compressors used in the SF_6 pumping system was defective and was returned to the factory for a warranty repair. We were able to continue operation of the Dynamitron using the remaining two compressors. The unit has been returned and is now back in service.

To reduce ripple on the high-voltage terminal, the SF_6 recirculating fans and motors inside the main Dynamitron tank were replaced with new motors and squirrel-cage blowers. This has considerably decreased mechanical vibrations of the terminal in the rf field and has led to a corresponding decrease in the amplitude of the terminal voltage ripple.

The Dynamitron technical staff spent some time developing an ion source that uses supersonic expansion cooling of electronically-excited radicals. This was temporarily put aside and modifications were made to electrode structure of the conventional duoplasmatron ion source. In this mode of operation, electrons are produced by direct heating of the filament, however they are then confined to this region by holding fields. Those electrons which drift into the usual plasma region, are accelerated and impact the source gas (at a pressure of about 50 mTorr) in the entrance to the extraction region. The resulting ions are then extracted and accelerated. Because the ionizing electrons are nearly monoenergetic (the spread is found to be about 0.3 eV) this procedure, when used with methane as the source gas, provided a beam of CH_4^+ ions with excitations believed to lie in a narrow band near the ground state. Experiments with this ion beam have provided the first experimental determination of the stereochemical structure of the CH_4^+ ground state.

The accelerator improvements made during the past few years have measurably increased the Dynamitron performance. We can now quickly go to 4.0 MV and we routinely run for long periods of time at 4.5 MV and higher. Before these improvements, we were not able to operate above 4.0 MV. Although we have accelerated 9 microamperes of beam at 4.8 MV, the capabilities of the Dynamitron at voltages above 4.5 MV have not yet been fully explored.

The Dynamitron console computer has been running very reliably for the past year. It monitors the control console and takes logs of various parameters which can easily be recalled. This is especially needed now since the machine is not always operated by Dynamitron personnel. It is also used to calculate magnet settings for the various beams of ions accelerated by the Dynamitron. Several improvements have been made during the past year. The reliability of the computer program has been greatly improved and many more control console parameters are automatically read by the computer. Some of these are the magnetic fields of the bending magnets, target and shutter currents, SF_6 pressure, and the ion-source gas.

The old PDP-11/45 data-acquisition computer system has been removed. The VAX-11/750 computer system has been operating reliably and is used routinely for both data acquisition and analysis as well as control of experimental equipment.

3. University Use of the Dynamitron

(B. J. Zabransky)

The Argonne Dynamitron continues to be a valuable research facility for scientists from outside institutions. It is not only the accelerator itself that attracts outside investigators but also the unique associated experimental equipment as well as the on-going research programs being conducted at the Dynamitron.

Most visiting scientists chose to collaborate with local investigators on problems of common interest. A few, however, worked as independent groups. Some came for a one-time-only experiment, but most are participants in research programs that have spanned longer periods.

During the year nine scientists came from eight outside institutions to use the Dynamitron. They came from five states and two foreign countries. They participated in experiments that used 32% of the time scheduled for research. A list of those institutions from which outside users of the Dynamitron came during 1986 is given below. The list includes the name of the institution, the title of the research project, and the name of the principal investigators at each institution. The names of their Argonne collaborators (if any) are enclosed in parentheses.

(1) Fermi National Accelerator Laboratory, Batavia, Illinois
Nonresonant Capture of Protons by ^{27}Al
A. Elwyn, G. Hardie,* R. E. Segel†

(2) Illinois Institute of Technology, Chicago, Illinois
The Effects of Radiation Damage on the Superconducting Properties of NbN and VN
J. Zasadzinski, R. Vaglio‡ (D. Capone, R. Kampwirth, K. Gray)

(3) Marquette University, Milwaukee, Wisconsin
Radiation Damage of Covalent Crystal Structures
L. Cartz, F. G. Karioris, M. Wang, M. S. Wong

(4) Millersville State University, Millersville, Pennsylvania
A Measurement of the Structure of N_2^{++}
P. J. Cooney (G. Both, E. P. Kanter, Z. Vager, B. J. Zabransky)

(5) Northwestern University, Evanston, Illinois
Nonresonant Capture of Protons by ^{27}Al
R. E. Segel, G. Hardie,*, A. J. Elwyn¶

(6) University of Notre Dame, Notre Dame, Indiana
Beam-foil Spectroscopy of $Ne^{6+, 7+, 8+}$
A. Livingston, A. Mazure (H. G. Berry, L. Engström, C. Kurtz)

(7) University of Salerno, Italy
The Effects of Radiation Damage on the Superconducting Properties of NbN and VN
R. Vaglio, J. Zasadziniski§ (D. Capone, R. Kampwirth, K. Gray)

(8) Western Michigan University, Kalamazoo, Michigan
Nonresonant Capture of Protons by ^{27}Al
G. Hardie, R. E. Segel,† A. J. Elwyn†

*Western Michigan University, Kalamazoo, Michigan.
†Northwestern University, Evanston, Illinois.
‡University of Salerno, Italy
¶Fermi National Accelerator Laboratory, Batavia, Illinois
§Illinois Institute of Technology, Chicago, Illinois

The Resident Graduate Student Program is open to students who have finished their course work and passed their prelims. They come to Argonne and perform their Ph.D. thesis research here. One member of this program worked at the Dynamitron during 1986. He participated in experiments that used 7% of the time allotted to research. Those who used the accelerator are listed below, together with their home university and their local thesis advisor.

(1) J. Camp, University of Chicago
G. T. Garvey, advisor

In addition, the following graduate students, undergraduate students and pre-college students have participated in research based at the Dynamitron.

Graduate Students

(1) D. Baran, Western Michigan University
G. Hardie, advisor

(2) G. Gerino, Northwestern University
R. Segel, advisor

(3) A. Mazure, University of Notre Dame
A. Livingston, advisor

(4) M. Saber, Northwestern University
R. Segel, advisor

(5) M. Wang, Marquette University
L. Cartz, advisor

(6) M. S. Wong, Marquette University
L. Cartz, advisor

(7) D. Zajfman, The Technion, Israel
E. P. Kanter, advisor

Undergraduate Students

(1) M. Batek, University of Illinois at Urbana
B. J. Zabransky, advisor

Pre-College Students

(1) I. Huberman, Lyons Township High School
E. P. Kanter, advisor

ATOMIC AND MOLECULAR PHYSICS RESEARCH

Introduction

Atomic Physics research in the Physics Division consists of the following ongoing programs:

(1) High-resolution laser-rf spectroscopy with atomic and molecular beams (W. J. Childs),

(2) Beam-foil research, ion-beam/laser interactions, and collision dynamics of heavy ions (H. G. Berry, L. Young, and W. J. Childs),

(3) Interactions of energetic atomic and molecular ions with solid and gaseous targets (E. P. Kanter and Z. Vager),

(4) Theoretical atomic physics (Currently staffed by Visiting Scientists), and

(5) Atomic physics at ATLAS (R. W. Dunford and H. G. Berry)

During 1986 research in our atomic physics programs continued at a vigorous pace. A major milestone of note was the completion of "BLASE" and the achievement of the first experimental results with this new laser/ion-beam interaction facility. Another highlight during 1986 was the use of the new "MUPPATS" detector to perform the first direct measurements on the geometrical structures of the CH_4^+ and $C_2H_3^+$ molecular ions. In addition, the high-resolution laser rf-spectroscopy program was able to extend its extremely high precision to measurements on atomic ions during the past year.

In the course of 1986 and early 1987 a new research program was established to take advantage of the outstanding opportunities for atomic physics at ATLAS. Robert W. Dunford, from Princeton University, was hired to head up this effort. He joined the staff in September 1986. Although there had already been some atomic physics use of ATLAS by both ANL staff and outside users, we anticipate that through the creation of this new program a much higher level of use of ATLAS will ensue in such a way as to take full advantage of the unique opportunities that are presented by that accelerator. A special atomic-physics beam line at ATLAS has recently been completed through Accelerator Improvement Project funding.

In addition to the high-energy beams from ATLAS itself, we shall have available, beginning in the late summer of 1987, intense low-energy beams of atomic and/or molecular ions from an ECR ion source now being constructed for the new positive-ion injector for ATLAS. This source, capable of producing atomic-ion beams in very highly-charged states, will be located on a 350-kV high-voltage pedestal thereby providing Argonne with a unique facility for attacking a wide range of new and interesting problems in both spectroscopic and collisional atomic physics. We believe that this facility will prove to be so productive for atomic physics that the associated research will warrant continuation beyond 1989, the time when the present ECR source is scheduled for use with the new ATLAS injector. We are therefore planning to submit a proposal for additional equipment funds for the construction during 1989 of another ECR source for use on an existing high-voltage platform that is currently associated with the Physics Division's tandem accelerator but expected to be available in 1989.

Over the past year or so there has been a significant "sociological" change in the conduct of our atomic physics programs. We now have vastly increased collaborations between staff members who until recently conducted essentially independent research programs. This has greatly enhanced the cohesion of our overall program and the communication within it. For example, Dr. Childs, his post-doc, and scientific assistant now spend a large fraction of their time collaborating with Drs. Berry and Young and their associates on the study of ion-beam/laser interactions at the newly completed BLASE facility. Dr. Young has also worked closely with Dr. Childs on the laser-rf spectroscopy of LaO. Further, Drs. Dunford, Berry and Kanter have worked together and with several non-Argonne scientists in varying collaborations to tackle problems of mutual interest that exploit the high-energy ion beams available from ATLAS. Drs. Dunford and Berry jointly are organizing the new atomic physics thrust to use the ATLAS ECR ion source on a 350-kV high-voltage platform. Dr. Young's expertise in laser technology is being utilized in setting up the laser system that will be employed in conjunction with the ECR program. A further significant contribution of Dr. Young lies in her work with our nuclear physics program in the development and construction of a polarized deuterium target designed for use with storage rings.

An important goal in our atomic physics program is the re-establishment of an ongoing resident research program in theoretical atomic physics. We are continuing to make every effort to identify and hire a suitable candidate with a strong interest in atomic/molecular theory. In the meantime, our theory effort has been staffed primarily through a series of distinguished visitors. Charlotte Froese Fischer of Vanderbilt University, together with one of her theory students, spent the period from January 1 through June 30, 1986 on sabbatical leave with our Atomic Physics program. Chris Bottcher, ORNL, has joined us for a twelve-month period that began in September 1986. Chii-Dong Lin, Kansas State University, joined the Division for a four-month period beginning in September 1986. Independently we have arranged forR. Stephen Berry of the Department of Chemistry, The University of Chicago, to hold a continuing joint appointment with the University and the Argonne Physics and Chemistry Divisions. Professor Berry and his students spend approximately one month per year at Argonne interacting with programs in the two Divisions. Arrangements have been made for Dr. Gregory Natanson, Northwestern University, to spend three months with our Atomic Physics program during the summer of 1987.

On April 2, 1986, Dr. L. S. Goodman retired after 40 years of service at Argonne. For the past several years, Dr. Goodman has been collaborating with Dr. W. J. Childs in a highly successful program of research in rf-laser double-resonance spectroscopy. Although now retired, Dr. Goodman continues to show a keen interest in our research programs.

On February 1, 1987, the program of Dr. J. Berkowitz in photoionization-photoelectron research was transferred from the Physics Division's Atomic Physics program to the Chemistry Division's Chemical Physics program.

Over the past several months the ANL Atomic Physics group has been active in organizing several workshops and conferences. A U.S.-Japan seminar on "Physics with Fast Molecular Ion Beams" was held in Hawaii, December 16-20, 1985, and a workshop on "Rydberg States of Highly-charged Systems" was held at Argonne, June 16-17, 1986. Atomic-physics presentations were also made at the ATLAS Users' Workshop and open PAC meeting held at Argonne, October 2-3, 1986. (The Program Advisory Committee for ATLAS has recently been augmented to include an atomic physicist. Professor C. L. Cocke, Kansas State University, is currently serving.) On January 12-13, 1987, a workshop on "Opportunities in Atomic Physics using Slow, Highly-charged Ions" was held in the ANL Physics Division. This workshop was of particular benefit in providing guidance for possibilities that can be pursued in connection with the ECR ion source soon to be available at ATLAS. From March 16-17, 1987, a workshop on "Supercomputers in Atomic, Molecular, and Optical Physics" will be organized at Argonne by our Atomic Physics group.

VI. HIGH-RESOLUTION LASER-rf SPECTROSCOPY WITH ATOMIC AND MOLECULAR BEAMS

The atomic-beam laser-rf double-resonance technique provides a way for making extremely precise measurements of energy splittings in atomic, molecular and ionic systems. When used selectively to study families of related atoms or molecules it exposes the underlying trends clearly and has in recent years been very important in stimulating new ab initio calculations. This iterative process continues to lead to significant improvements in the theory.

We have devoted considerable effort to studying the spin-rotation and hyperfine interactions in alkaline-earth monohalides and more recently, the (isoelectronic) group IIIa monoxides. These have been chosen as a logical starting point for high-precision molecular studies because they are basically ionic systems with a single electron outside closed shells, and therefore relatively approachable theoretically. In addition to measuring the spin-rotation and hfs interactions themselves, the rotational and vibrational dependences have been determined. Performing the rf transitions in an electric field has led to measurement of the electric-dipole moments (through the Stark Effect), thereby stimulating considerable further theoretical efforts. The availability of such high-precision data has recently led to the use of super computers for the ab initio theory with promising results.

Systematic, high-precision measurements of the hfs of neutral, many-electron atoms have recently led to adaption of the Multiconfigurational Dirac-Fock (MCDF) ab initio theory to make possible hfs calculations in heavy atoms. Comparison of the theoretical and experimental results, especially our ^{139}La I results of this past year, reveal completely unexpected deficiencies in the theory. Some of these are fundamental in nature and will hopefully lead to a real improvement in the theory.

We have been developing, in parallel with the programs outlined above, a new apparatus to allow us to extend our high-precision laser-rf double-resonance studies to beams of slow ions. In this just-completed apparatus, the ion (1.35 keV) and laser beams are collinear and first results with beams of $^{151,153}Eu^+$ show linewidths of only 60 kHz, far sharper than observed in any other ion-beam apparatus.

a. **Hyperfine Structure of $^{151,153}Eu^+$ in the States $4f^7(^8S)5d\ ^9D_J$ by Collinear Laser and rf Double Resonance**
(A. Sen, L. S. Goodman, W. J. Childs, and C. Kurtz)

A new apparatus has been constructed for laser fluorescence and laser-rf double-resonance studies of slow ion beams. The laser and ion beams are collinear after magnetic mass analysis of the ion beam. The ion energy is kept as low (1.35 keV) as is consistent with reasonable ion optics in order to maximize the transit time through the 50-cm long rf region. Because of the extremely long (~ 12 μs) transit time achieved, the linewidth observed for $\Delta F = \pm 1$ magnetic dipole hfs transitions is only 60 kHz, by far the narrowest so far observed for ion beams. Hyperfine splittings can thereby be measured to ± 1 kHz, about 10^3 better than can be done by laser techniques alone. Measurements have been made of these splittings in 5 excited states of $^{151,153}Eu^+$. A short report on the technique and the initial success has been submitted for publication, and a longer paper including a detailed theoretical analysis of the results is being prepared.

Figure VI-1 shows a typical radiofrequency hyperfine transition in a metastable atomic state of $^{151}Eu^+$. The transition occurs twice, corresponding to the direct rf wave (travelling with the ion beam), and the reflected wave (travelling against the ion beam). The separation of the peaks is twice the rf Doppler shift, and the resonance frequency for the ions at rest is midway between the two peaks.

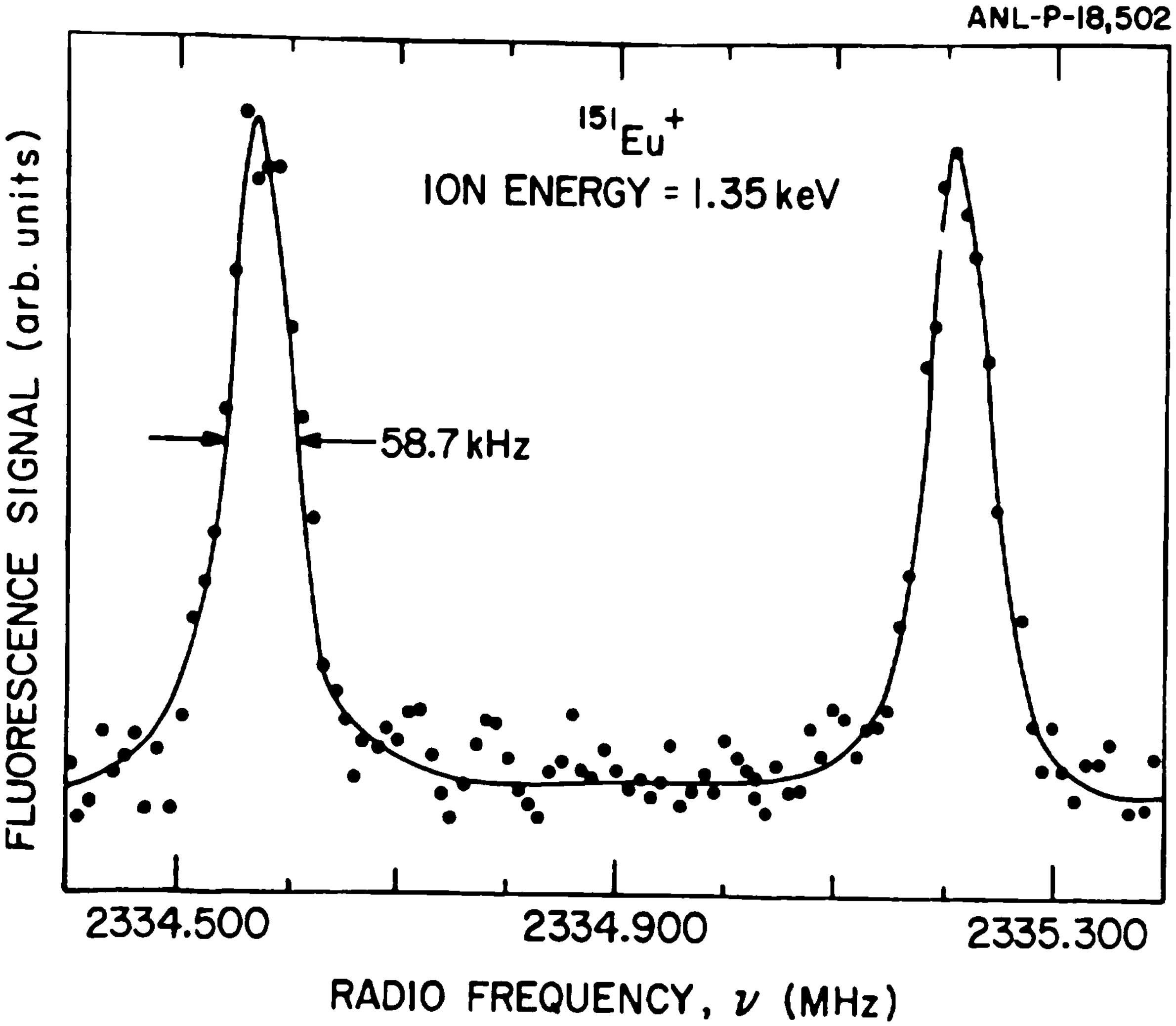


Figure VI-1. Radiofrequency hyperfine transition in a metastable atomic state of $^{151}Eu^+$ observed as a resonant increase in fluorescence. The two peaks correspond to the direct and reflected rf waves (travelling with and against the ion velocity) and are separated by twice the rf Doppler shift. The resonant frequency for the ions at rest is midway between the peaks, and can be determined to ±1 kHz with this technique. The precision is about 1000 times better than can be achieved by laser techniques alone.

b. **Fine and Magnetic Hyperfine Structure in A $^2\Pi$ and X $^2\Sigma^+$ States of Yttrium Monoxide** (W. J. Childs, T. C. Steimle,* and O. Poulsen†)

The spin-rotation and hyperfine interactions of YO have been studied in a continuation of our program involving group IIIa monoxides. Results were obtained for both the ground X $^2\Sigma^+$ and excited A $^2\Pi$ states. Although the interpretation is not yet complete, the results for the ground-state spin-rotation interaction strength γ are of great interest. We find γ is negative, in contrast to the situation for all other isoelectronic molecules studied. This is very difficult to understand, but may arise from low-lying 3-electron states. *Ab initio* calculations have not predicted any such perturbing state, however, and our result will require more detailed theoretical effort for explanation. The availability of super computers may soon make such calculations feasible. We also find that γ has a very strong vibrational dependence, indicating that the perturbing state is extremely close to the ground state. Analogous work on the even lighter isoelectronic system ScO is now underway in an effort to see if the anomaly is also present there. A paper on the YO work is being prepared for submission.

Figure VI-2 shows the observed vibrational dependence of the spin-rotational interaction γ_0 in the X $^2\Sigma^+_{1/2}$ electronic ground state of YO. The interaction strength is plotted in MHz against the vibrational quantum number v. The uncertainty is much smaller than the diameter of the points.

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*Department of Chemistry, Arizona State University, Tempe, Arizona
†Institute of Physics, University of Aarhus, Aarhus, Denmark

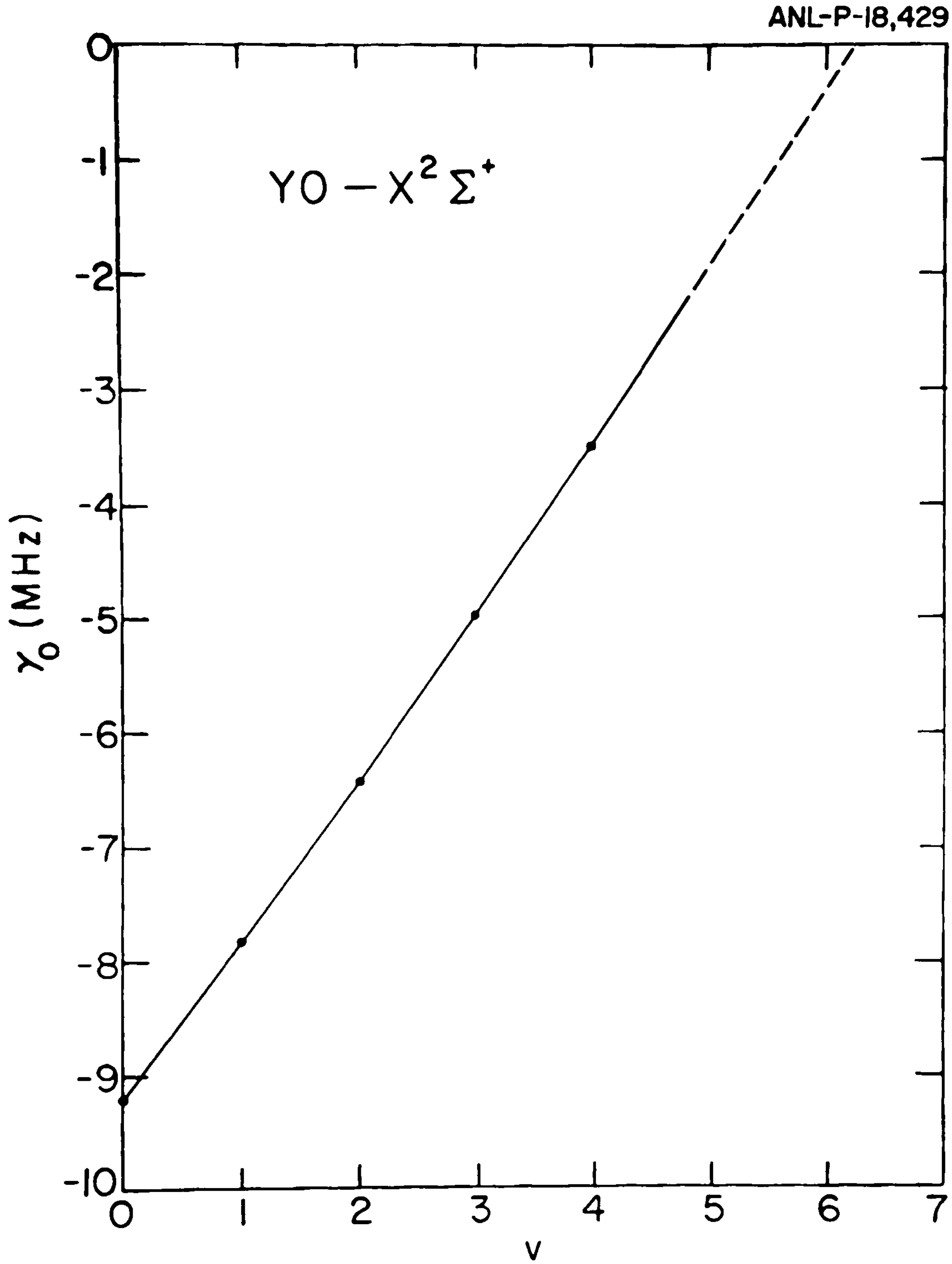

Figure VI-2. Plot of the spin-rotation interaction strength γ_0 in the $X\ ^2\Sigma^+_{1/2}$ electronic ground stdate of YO plotted against the vibrational quantum number v. That γ_0 is negative for v = 0 is completely unexpected, and implies the existence of unknown perturbing states near the ground state. The strong sensitivity of γ_0 to the vibrational states implies that the perturbing state is extremely close to the ground state.

c. **Further Studies of the $(5d + 6s)^3$ System of ^{139}La I, Including Comparison with MCDF Calculations** (W. J. Childs and U. Nielsen*)

New measurements of the hfs of highly excited states of the $(5d + 6s)^3$ electron system of La I have been compared with the *ab initio* MCDF theory. Serious discrepancies between theory and experiment are found in the case of contact hfs (hfs arising from s or $p_{1/2}$ electrons). For the $5d^2 6s$ configuration, the zero-parameter *ab initio* theory consistently underestimates the contact hfs. For the $5d^3$ configuration (where contact hfs is nominally absent) experiment shows that contact hfs plays a dominant role. Although this must arise from polarization of the inner s-shells, there is no systematic way of taking account of such effects within the current theory. The new measurements have played a vital role in uncovering these completely unexpected shortcomings of the MCDF theory (the only *ab initio* theory available for the hfs of heavy, many-electron atoms). The results call for other measurement of d-shell hfs including measurements in ions for comparison with the results for neutral atoms. A paper on the La work is being prepared for submission.

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*Institute of Physics, University of Aarhus, Aarhus, Denmark

VII. Ion-Beam/Laser Research, Beam-Foil Research, and Collision Dynamics of Heavy Ions

Our program consists of investigations of the structures and dynamics of atomic and molecular ions principally using photon detection techniques with accelerated ions.

The experiments are mostly at the "BLASE" facility, a recently-upgraded 20-150-keV accelerator system with high voltage stability suitable for fast-beam laser-interaction studies. Measurements are in progress on hyperfine structures of heavy atomic ions, of the production of metastable light atomic ions for laser studies of QED and relativistic effects, and the improvement of several different detection techniques.

Design of a new photo-fragment detection scheme for molecular ions is in progress, and may also be used in some of the atomic-ion experiments.

The atomic-structure measurements also use ions produced at the Dynamitron accelerator (0.5 - 4.5 MeV ion energy), and at the ATLAS (50 - 500 MeV) atomic-physics beam line.

a. **BLASE Upgrade** (L. Young, H. G. Berry, C. Kurtz and L. Engström)

We have completed a comprehensive upgrade of the BLASE (20 - 150 keV) facility. This has resulted in great improvements in two areas: (1) energy resolution, (2) mass resolution. The short-term energy stability has been improved from the specified 1 part in 10^3 of the initial high-voltage supply to 2 parts in 10^6 by incorporation of an active feedback system located on the high-voltage platform. The long-term energy drift has been improved from the original 0.2% per hour to 0.04% per hour. The mass resolution has been improved from 1 part in 50 to 1 part in 350 by a 90° analyzing magnet.

In addition, improvements have been made in ion-source operation with the use of stabilized power supplies, and precision leak valves. Stable operation on a single isotope of Sm II can be maintained at 200 nA of beam current for several hours. Ion-source operating parameters can be independently tuned for minimum energy spread with the aid of a beam pick-up aperture located at the end of the accelerator tube. With the highly-stabilized platform potential, we now have the situation in which essentially all the longitudinal velocity spread in the beam is due to the ion-source discharge conditions. We have been able to achieve Doppler widths of less than 14 MHz, ($\delta v/v = 3 \times 10^{-8}$) corresponding to energy spreads of less than 3 volts from the ion source while running ^{147}Sm II.

Finally, the complete rebuilding of the experimental area has resulted in major improvements in 1) mechanical stability of the beam line, 2) the amount of working space, 3) lighting of the work area, 4) accessibility of the dedicated mini-computer, and 5) temperature control (Dec. 1986).

b. <u>Hyperfine Structure in Sm II and Eu II</u> (L. Young, H. G. Berry, W. J. Childs, C. Kurtz and T. Dinneen*)

As an initial test case for the new BLASE facility, we chose to study hyperfine structure in Sm II within the $4f^6 5d$ configuration using collinear laser fast-ion-beam spectroscopy. A variety of levels lying within 2 eV of the ground state are populated within the ion source. Initial measurements of the levels within the $4f^6(^7F)5d$ configuration were extremely encouraging with respect to signal/noise and linewidth, but contained disturbing systematic errors. These were greatly reduced by eliminating stray electric fields in the observation region and by decreasing the rate of high-voltage drift by a factor of 50. The reduced widths are indicated in Fig. VII-1. The improvement in our precision was checked by making similar measurements in Eu II and comparing our results with recent highly-precise rf resonance measurements of Sen and Childs (see their report). We are now beginning a systematic study of levels in the $4f^6(^7F)5d\,^8H$ multiplet which are 99% LS coupled, for comparison with <u>ab initio</u> Hartree-Fock theory.

*Graduate Student from the University of Chicago, Chicago, Illinois

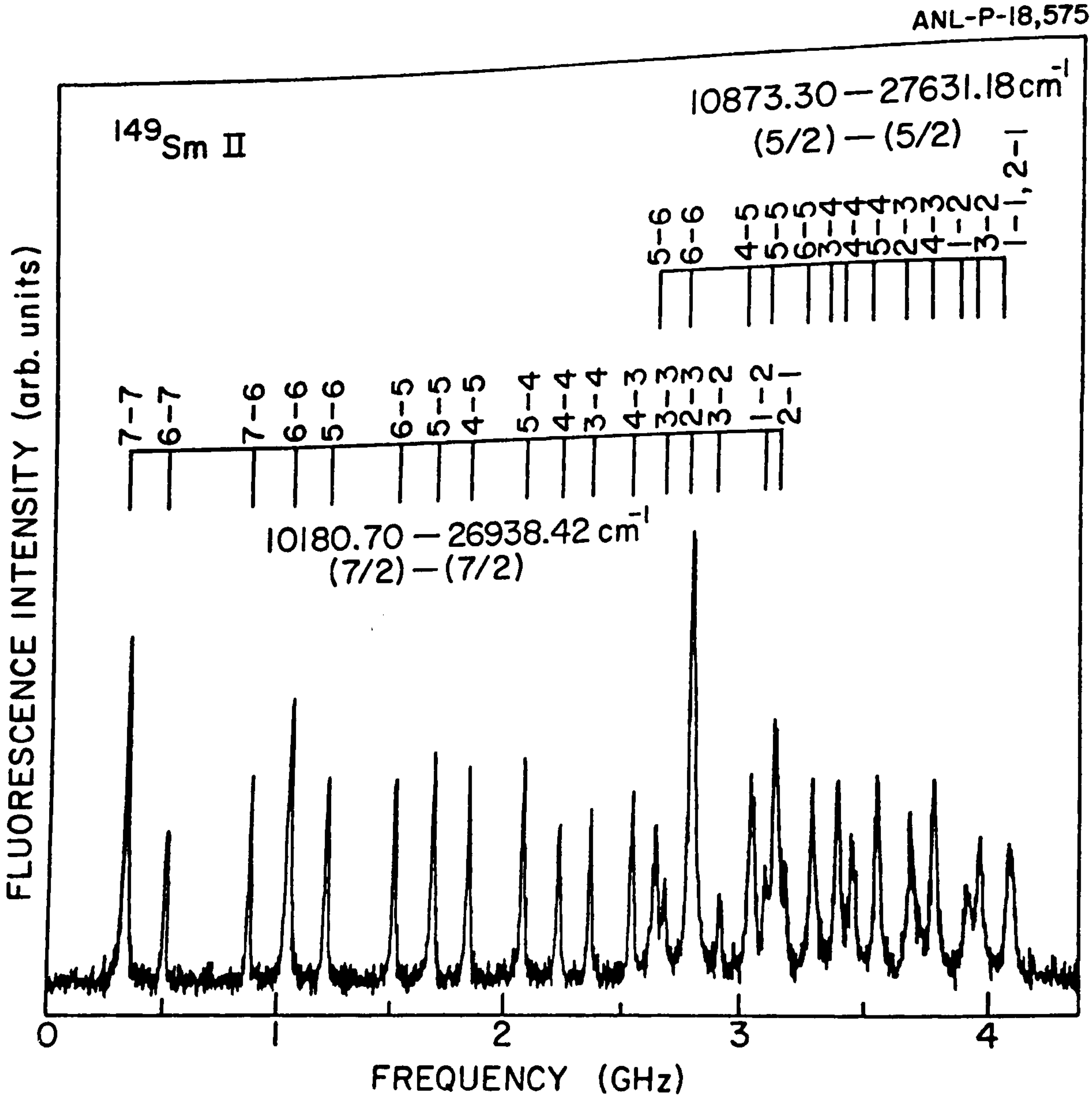

Fig. VII-1. Hyperfine structure of two overlapping transitions in samarium II which lie within 3 GHz of each other. The linewidths are approximnately 25 MHz. Only one of these two transitions had previously been reported. The other was assigned from existing sets of energy levels.

c. <u>Alignment and Orientation Production in Hydrogenic States</u> (H. G. Berry and J. C. Dehaes*)

Further measurements have been made at Brussels in our investigation of the wave functions for fast beam-foil excited hydrogen states. The excitation distributions and the shapes of the wave functions depend on the foil interaction, and, more critically, on the final surface interaction. We have observed and now quantitatively verified the existence of a final-surface electric field which has a strong influence on the excited-state wavefunctions and their spatial anisotropy. In more recent experiments, we have studied variations with the state of the solid foil, and have succeeded in relating the observed changes in the excited-state wave functions with the number of secondary electrons produced in the foil. Further experiments with an improved high-vacuum system are underway.

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*Free University of Brussels, Brussels, Belgium

d. <u>Spectroscopic Analysis of the n = 3 levels of Ne-like Argon (ArIX)</u> (L. Engström and H. G. Berry)

A considerable interest has recently been focussed on the $3p^5 3s$, 3p and 3d levels along the Ne I isoelectronic sequence. For example, a promising scheme to achieve a XUV laser involves the $2p^5 3s$ - $2p^5 3p$ transitions in Ne-like ions. Futhermore, based on isoelectronic extrapolations of differences between experimental and theoretical wave numbers, twenty four lines in the solar-flare spectra have been identified as transitions between these configurations in Fe XVIII and Ni XIX.

In our work, high-quality Ar-spectra have been obtained with the beam-foil technique utilizing Ar^+ and Ar^{2+} beams accelerated to energies between 3 and 8.4 MeV at the Dynamitron. Comparisons of the relative intensities of the observed Ar lines at the different energies allow accurate charge-state assignments of the spectral lines. 33 lines (with a wavelength uncertainty of less than 0.05 A) have been identified as transitions between the 3s, 3p and 3d configurations in Ar IX, leading to the establishment of 24 out of the possible 26 energy levels. In addition, transitions between the core-excited $2s2p^6 3s$, 3p and 3d configurations in Ar IX as well as the $2p^4 3s$ 3p and 3d configurations in F-like Ar (Ar X) are also prominent in our spectra. The Ar IX study has been published,[1] and work is in progress on the analyses of the Ar VII and Ar X spectra.

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[1]Lars Engström and H. Gordon Berry, Physica Scripta 34, 131 (1986).

e. **Accurate Transition Probabilities for the Resonance Transitions in Na- and Mg-like Argon** (L. Engström, H. G. Berry and N. Reistad*)

The decay of the 3p $^2P_{1/2,3/2}$ and 3d $^2D_{3/2,5/2}$ levels in Ar VIII, and of the 3s3p ^1P, 3s3d ^1D, $3p^2$ ^1S and ^1D levels in Ar VII has been studied by the beam-foil technique, using the 4.5-MV Dynamitron accelerator.

Previous experimental measurements of the lifetime of the 3p ^2P and the 3s3p ^1P levels have shown considerable deviations from the values predicted by various modern theoretical calculations. In our study, we show that this discrepancy is due to the inability of the standard technique (curve-fitting) to extract the correct lifetime from the measured decay curves when these are severely perturbed by cascades. However, by measuring also the decay of the most prominent directly-cascading levels, 3d ^2D in Ar VIII and 3s3d ^1D, $3p^2$ ^1S and ^1D in Ar VIII, and explicitly including this information in the analysis (using the ANDC technique) accurate lifetimes are obtained.

The final 3p ^2P and 3s3p ^1P lifetimes are found to be in excellent agreement with the most recent theoretical results. The results of this study have been published.[1]

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*Department of Physics, Lund University, Lund, Sweden
[1]N. Reistad, L. Engström, and H. G. Berry, Physica Scripta 34, 151 (1986).

f. <u>Saddle-point Electron Production</u> (H. G. Berry, T. J. Gay,* R. E. Olson,* V. Irby,* and E. Hale*)

A well-known phenomenon of fast-beam collisions with gas targets is the production of convoy electrons moving at the same velocity as the target projectile. It has recently been suggested that a second peak in the secondary electron velocity distribution should occur close to the velocity of the center-of-mass energy of the beam-gas collision. This would produce electrons at approximately half the projectile velocities. We have named these "saddle-point" electrons since they are enhanced by the saddle-point produced in the potential distribution seen by electrons between the projectile and the target atom. The experiment incorporated a target chamber and detection equipment from the Argonne Dynamitron, and was set up at a low-energy (250-keV) accelerator at the University of Missouri. We measured the revelant (doubly-differential in energy and angle) scattered electrons in collisions of fast protons on a helium gas target, and observed the enhancements expected from the recent theory. Further measurements are being completed to map out these distributions for different projectile velocities, and also for other rare-gas targets. Results of this work are submitted for publication.

*Physics Department, University of Missouri-Rolla, Rolla, Missouri

VIII. INTERACTIONS OF FAST ATOMIC AND MOLECULAR IONS WITH SOLID AND GASEOUS TARGETS

Tightly collimated beams of atomic and molecular ions with energies variable in the range 0.5-4.5 MeV are directed onto thin (~30 Å) foil or gaseous targets. The distributions in laboratory velocities are measured with high resolution (~0.005° and ~600 psec) for the resultant ions. The major aim of the work is a general study of the interactions of fast ions with matter, but with emphasis on those aspects unique to the use of molecular-ion projectiles. In particular, we have been able to deduce the structures of the incident molecular ions. These two different aspects of the work are mutually interdependent. In order to derive structure information about a given molecular ion, one needs to know details about the way the dissociation fragments collectively interact with the target in which the dissociation occurs. Similarly, a knowledge of the structure of the incident molecular clusters is important in understanding the physics of their interactions with the target. Our work therefore began with careful studies involving beams of the simplest and relatively well-understood diatomic molecular ions (H_2^+, HeH^+, etc.). Even with these, several new and interesting phenomena have been encountered (e.g., the interactions between the molecular constituents and the polarization oscillations that they induce in a solid target, the marked difference in dissociations induced in gases as compared with those in foils, the anomalously high transmission of some molecular ions through foils, and striking electron-capture phenomena when compared to atomic ions). Now that those studies have given us a good grasp on the important physical processes affecting the penetration of molecular ions through matter, we have concentrated our efforts on using this knowledge to study the structures of the molecular-ion projectiles. The development of the multiparticle MUPPATS detector has enabled us to directly measure the densities of atomic nuclei within small polyatomic molecules. These experiments provide a radically new source of information on the structures and vibrations of molecular ions which has already made significant contributions in guiding theorists.

The bulk of our effort during 1986 was directed toward the study of several polyatomic molecular ions. These studies necessitated the development of several important new experimental techniques including ultrathin stripper foils and specialized ion sources. Furthermore, these studies have helped us to develop the necessary calculational tools to extract the most information from our measurements. Some of the highlights in 1986 included:

a. **Low-Energy Stereostructure of $C_2H_3^+$** (G. Both, E. P. Kanter, Z. Vager, B. J. Zabransky, and D. Zajfman)

The problem of determing the low-lying structures of protonated acetylene ($C_2H_3^+$) has received considerable attention in recent years by theorists and experimentalists alike. This interest is driven, in large part, by the important role such protonated hydrocarbons are thought to play in the chemical evolution of interstellar clouds. Unfortunately, laboratory spectroscopy of such molecules has been difficult. At the time our study commenced, the most extensive *ab initio* calculations predicted that the nonclassical "bridged" structure would lie lower (by only 0.7 kcal/mole) than the classical isomer. The experimental infrared spectra however had proven to be far too complex to resolve this question, or even to ascertain if either of these structural isomers manifested themselves in the data.

This proved to be a simple question to resolve with Coulomb-explosion measurements.[1] Our results (see Fig. VIII-1) clearly demonstrated that the nonclassical bridged structure dominated our sample of molecules. Although our analysis techniques are not yet sufficiently refined to discern small admixtures of rare structures, we have been able to place an upper limit of at most 15% of our sample displaying the classical structure (however this is merely an upper limit and the data are also consistent with none of that structure). This hinted very strongly that the theoretical predictions were incorrect. Further exploration of the potential surface in higher-order calculations have since verified that in fact the classical structure is not a potential minimum but rather a saddle point. Further studies are now underway to study the deuterated forms of this molecule.

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[1]E. P. Kanter, Z. Vager, G. Both and D. Zajfman, J. Chem. Phys. 85, 7487 (1986).

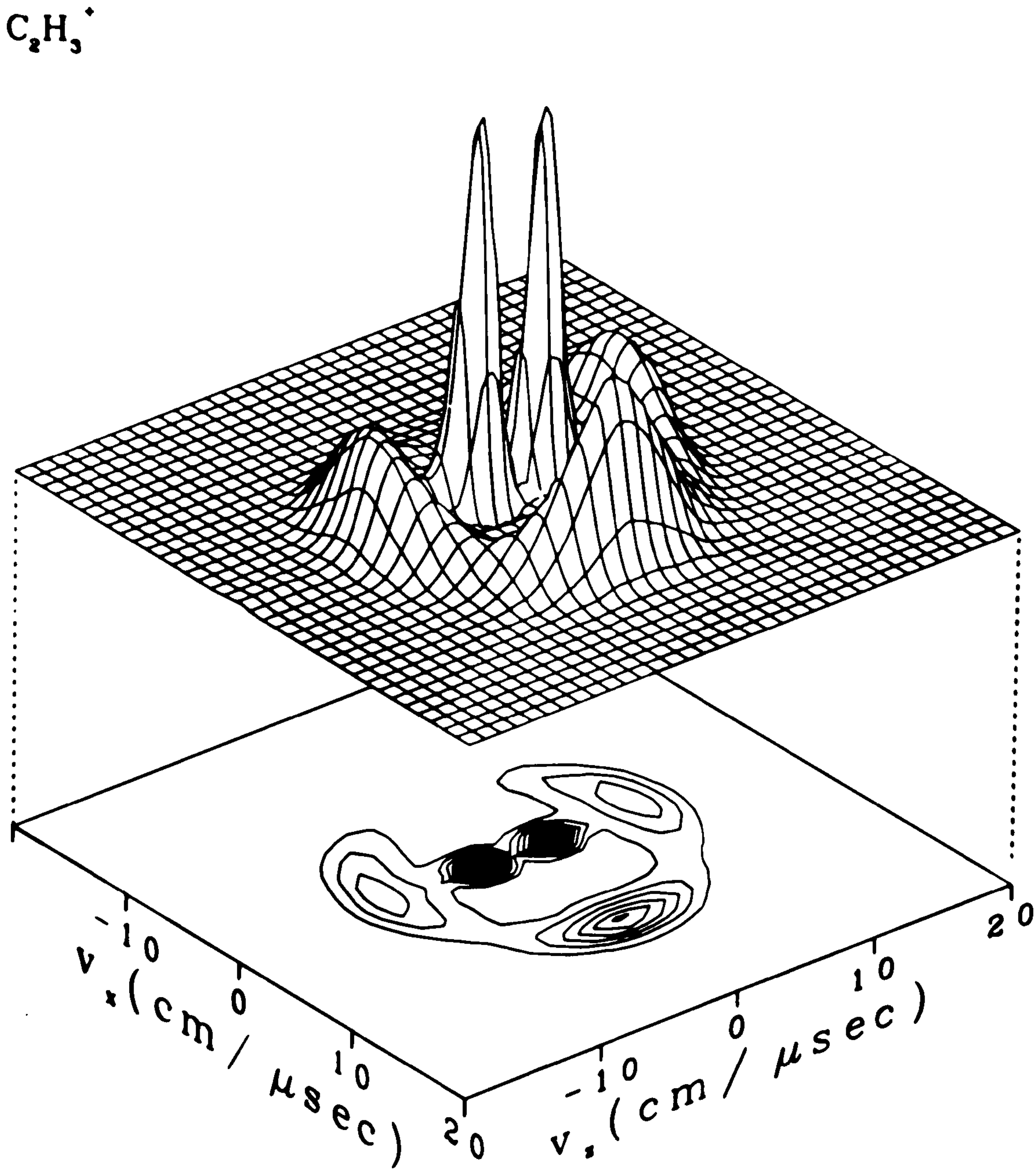

Fig. VIII-1. Plots of the densities of fragment ions in velocity space (relative to the mean carbon-ion valocity). The carbon-ion densities have been artificially reduced by a factor of 5 for display purposes. Above: isomeric display of the density projected onto the XZ plane. Below: contour plot of same data.

b. **Direct Determination of the Stereochemical Structure of CH_4^+** (G. Both, P. J. Cooney, E. P. Kanter, Z. Vager, B. J. Zabransky, and D. Zajfman)

CH_4^+ has been the subject of numerous theoretical and experimental papers. One of the major reasons for the interest in CH_4^+ is that it is one of the simplest cases in which a Jahn-Teller distortion from symmetry is predicted. Despite this well-known prediction, its structure had not hitherto been established. To display the Jahn-Teller effect in CH_4^+, we project our Coulomb-explosion data in the following manner. For every event, the two protons for which the HCH angle is minimal are selected and indexed as 1 and 2. The molecule is rotated so that the bisection of that angle lies on the z axis, with the molecular center-of-mass at the origin, and these two protons lie in the x-z plane. Following this event-by-event transformation, the other two protons (3,4) are found to lie mainly below the x-y plane and the groups are not distinguished in the x-z projection (see Fig. VIII-2a). In this y-z projection (Fig. VIII-2b), the proton groups 3 and 4 are well separated and the nonequivalence of the (1,2) and (3,4) proton groups is evident. These data clearly demonstrate the C_{2v} symmetry of the molecule and rule out the D_{2d} structure. This observation is consistent with recent findings of electron-spin-resonance (ESR) spectroscopy which suggest a dynamical Jahn-Teller distortion leading to the C_{2v} structure.

The Coulomb-explosion data, however, go further than just verifying the symmetry. When analyzed with more refined quantitative techniques, these data have allowed us to measure not only mean geometries (bond lengths and bond angles), but the deviations within our sample from those averages, and hence we deduce the full 9-dimensional vibrational wave function of the molecule. Preliminary results have been obtained with such techniques for the case of CH_4^+. The results show[1] that although the detailed structure is somewhat changed as one would expect, the difference in that case was minor and did not affect the symmetry group classification obtained in the simple qualitative analysis. Our results demonstrate the power of these techniques not only to study mean geometries of polyatomic molecules, but also to observe

[1] Z. Vager et al., Phys. Rev. Lett. 57, 2793 (1986).

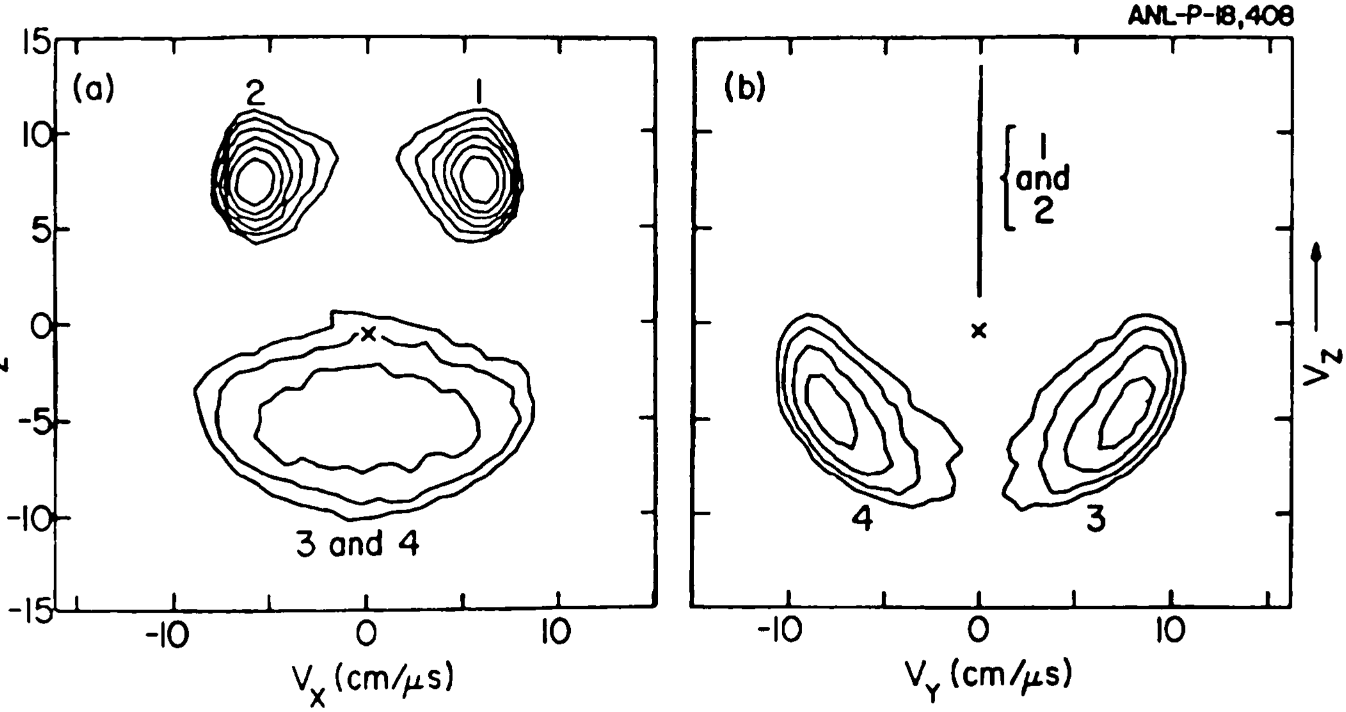

Fig. VIII-2. Contour plots of the densities of protons in velocity space (relative to the projectile center of mass) following the event-by-event rotations described in the text. The ensemble mean for the carbon-ion position is marked by (x). The data consist of five-fold coincidences between four protons and one C^{3+} ion for each event. (a) Projection on the X-Z plane as defined in the text. (b) Projection on the Y-Z plane. Contour levels are at 1.5%, 2.5%, 4%, 7%, 11% and 19% of the peak intensity.

directly the vibrational motions of the constituent nuclei. With proper analytical tools, it should be possible to derive and classify the normal modes of molecular motion. This radically new approach to molecular structure gives results that complement the precise information obtained from spectroscopy, when available.

c. **Ultrathin Foils for Coulomb-explosion Experiments** (G. Both, E. P. Kanter, Z. Vager, B. J. Zabransky, and D. Zajfman)

Because the maximum voltage of the Dynamitron accelerator sets a limit on the velocities of projectiles used in our experiments, previous attempts to study heavier molecular ions (such as $C_2H_3^+$ and CH_4^+) had been severely limited by the effects of multiple scattering in the stripping foil. This had not been a limitation in our experiments with lighter ions such as H_2^+ and HeH^+. However with heavier molecules, multiple scattering is the ultimate limitation in our efforts to study molecular vibrations. Ideally, one desires to reduce the effects of multiple scattering to about half that caused by bond-length variations due to zero-point vibrations within the molecule. As an example, for H_2O^+, this means the stripper must be less than about 0.5 $\mu g/cm^2$.

A further advantage of such ultrathin foils is that only a small portion of the Coulomb explosion takes place within the foil, and thus various approximations used to treat the motion of the nuclei within the foil, are less important in our quantitative analyses and thus our accuracy is improved. For these reasons, we have investigated various approaches of producing ultrathin stripping foils. Commercially-obtained carbon foils, with a nominal thickness of 0.2 $\mu g/cm^2$ always proved to be thicker than 1 $\mu g/cm^2$, despite various forms of surface treatments which we applied. This is attributed to the strong adsorption of carbon surfaces. We eventually succeeded in producing Formvar films of about 0.3 $\mu g/cm^2$ supported on high-transparency nickel grids.[1] Such films have proved adequately thin for all of the molecules we have studied so far (see Fig. VIII-3). As indicated above, such films are now adequately thin to permit the observation of zero-point vibrations in most molecules.

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[1] G. Both et al., Rev. Sci. Instrum. 58, 424 (1987).

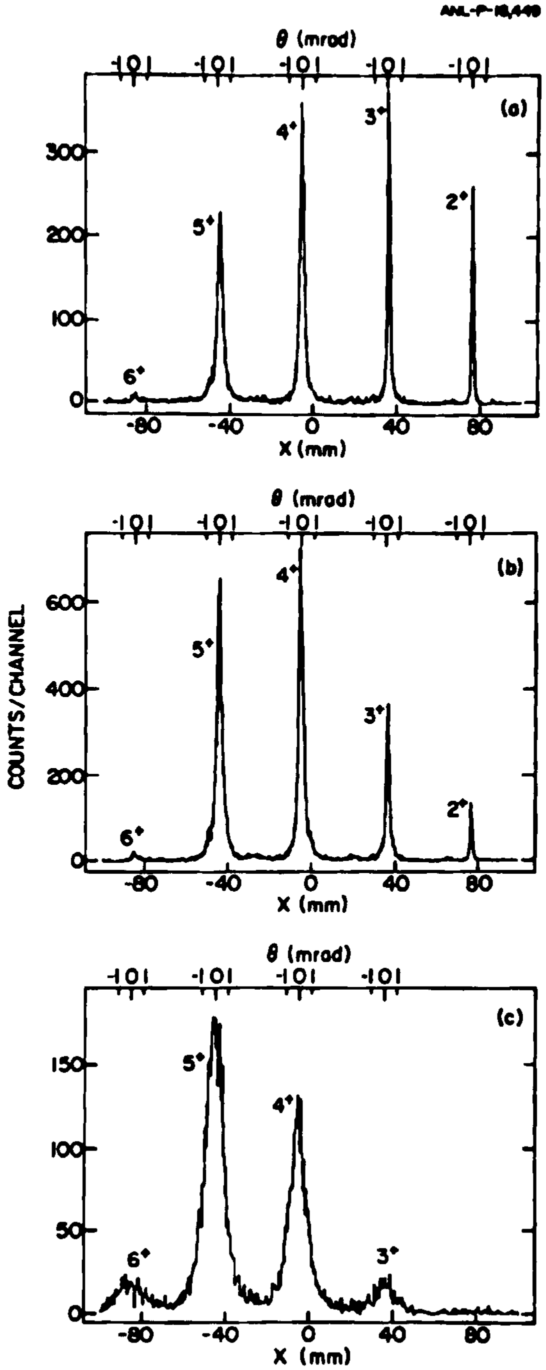

Fig. VIII-3. Charge-state resolved multiple scattering distributions of 4.5-MeV O^+ penetrating Formvar foils, (a) 0.5 μg/cm^2 thick, (b) 0.8 μg/cm^2 thick. The charge states of the emerging ions are indicated at the peaks. The lower abscissas give the position x on the detector, the upper ones the multiple scattering angle θ centered on each charge peak. Both distributions are in pre-equilibrium, but the difference is obvious. For comparison: (c) charge-state resolved multiple scattering distributions of 4.5-MeV O^+ penetrating a carbon foil, 3.5 μg/cm^2 thick.

d. **Charge-exchange and Multiple Scattering in Ultrathin Foils** (G. Both, E. P. Kanter, Z. Vager, and D. Zajfman)

As part of our effort to obtain ultrathin stripper foils, new techniques were necessitated to characterize the foil thickness. Our conventional measure, the observed multiple-scattering widths of transmitted heavy ions, proved inadequate when foils become so thin that statistical treatments of the scattering, and charge-changing processes become invalid. In particular, for foils thinner than 1 $\mu g/cm^2$, there is a strong charge-state dependence to the multiple scattering widths along with a corresponding shift in the charge-state distributions away from equilibrium.

In order to deal quantitatively with these data, a Monte-Carlo method was applied to describe the penetration of fast heavy ions through ultrathin films. A screened Coulomb potential was taken for the scattering process and geometric cross sections for the charge-exchange processes. The only free parameter in these calculations is the target thickness. We have demonstrated that with this one parameter, it is possible to fit simultaneously the measured non-equilibrated charge-state distributions as well as the angular distributions of the emerging ions. These simulations indicate that such ultrathin targets can approach single-collision conditions for atomic collision studies.

e. **Ion Source Development** (G. Both, A. Ruthenberg, L. Tack, Z. Vager, and B. J. Zabranksy)

We have investigated various schemes appropriate for sources of state-selected molecular ions in the Dynamitron high-voltage terminal. Several experiments have been carried out this year with molecular-ion beams produced by low-energy electron impact in the terminal. For example, for the CH_4^+ experiments, such a source was constructed by modification of the electrode structure of a conventional duoplasmatron ion source. In this mode of operation, electrons were produced by direct heating of the filament, however they were confined to this region by holding fields. Those electrons which drift into the usual plasma region, are accelerated and impact the methane gas (at a pressure of about 50 mTorr) in the entrance to the extraction region. The resulting ions are then extracted and accelerated. Because the ionizing electrons are nearly monoenergetic (the spread is found to be about 0.3 eV), this procedure provided a beam of CH_4^+ ions with excitation believed to lie in a narrow band near the ground state.

Work has also begun on a photoionization source to select higher-lying vibrational excitations. This source consists of an intense UV lamp to photoionize the sample gas, and a large-acceptance orange-peel spectrometer to momentum analyze the detached photoelectrons and thus tag the resultant ions. The spectrometer has now been completed and is currently being tested.

IX. THEORETICAL ATOMIC PHYSICS

The Atomic-Physics program in the Physics Division normally includes a theoretical component. Following the departure of K. T. Cheng (ab initio atomic structure theory) and G. L. Goodman, (part-time consultant on various molecular and atomic problems) from the Physics Division in 1985, we have made substantial efforts to locate a suitable strong candidate to re-establish a resident program in theoretical atomic physics. While this process continues we have been successful in attracting a series of outstanding atomic/molecular theorists who spend sabbatical visits with us. From January 1 through June 30, 1986, Dr. Charlotte Froese Fischer of Vanderbilt University (together with one of her theoretical students, Tomas Brage) visited the atomic physics group. Professor Chii-Dong Lin, Kansas State University, joined us for a four-month period beginning September 1986. Dr. Chris Bottcher, ORNL, joined us for a twelve-month period beginning also in September 1986. In December, 1986, Dr. Derek Richards of the Open University, England, visited for two weeks. He gave a series of lectures on Rydberg atoms and performed some collaborative research with Dr. M. Peshkin of the Physics Division. In addition, we have arranged for Professor R. Stephen Berry of the Department of Chemistry, University of Chicago, to hold a continuing joint appointment with the Argonne Physics and Chemistry Divisions. Professor Berry and his students spend approximately one month per year at Argonne. Arrangements have been made to have Dr. Gregory Natanson (Northwestern University) spend three months as a visitor with our atomic physics group during the summer of 1987. Dr. Natanson is particularly interested in working on problems relating to the "Coulomb-explosion" research currently being pursued at Argonne.

a. **Atomic Structure Calculations** (C. Froese Fischer* and T. Brage†)

i. Na I and Mg II Core Excited Quartet States

Experimental determinations of the lifetimes of some core-excited quartet states in Na I prompted us to investigate states of this type in Na I and Mg II. Bound-state wavefunctions had previously been determined. However, since autoionization is an important decay mechanism for many levels, calculations on the autoionization properties of these states were performed. Results of the work were presented at the Meeting of the Division of Electron and Atomic Physics held at Eugene, Oregon, June 18-20, 1986, and a paper is under preparation for publication.

ii. ^3P Levels in S I Above the Ionization Limit

A number of theoretical studies of the $3s3p^5\ ^3P$ level in S I (and also the $4s4p^5$ level of Se and the $5s5p^5\ ^3P$ level of Te) predict the level to be in the bound spectrum. J. Berkowitz and his collaborators have investigated the photoionization spectra of these atoms and noticed what appears to be a perturber in the region above the ^4S and ^2D ionization limits. They have suggested that this perturber is, in fact, the $3s3p^5\ ^3P$ level in S I and the $5s5p^5\ ^3P$ level in Te I.

Computations were undertaken to investigate not only the $3s3p^5\ ^3P$ level, but the entire sequence of ^3P levels up to (^2D) 7d ^3P. The $3s3p^5\ ^3P$ level was predicted to be in the bound spectrum close to the energy tabulated in the Atomic Energy Level tables. The perturbation appears to be the result of a confluence of three Rydberg series, the members being (^2P) 3d, (^2P) 5s, and (^2D) nd, n = 6 and 7. The ^3P levels are forbidden to autoionize in the absence of spin-orbit interaction. As a result, a further study to explain the observed photoionization intensities would require the inclusion of the latter interaction. A paper describing the work on the ^3P levels is in preparation.

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iii. Lifetimes of the $4s^2nd$ ^2D levels of Ga I

Experimental lifetimes of ^2S, ^2P, ^2D Rydberg series have been determined at Lund University. The ^2D Rydberg series is of special interest in that the lifetimes do not obey the usual $(n^*)^3$ trend. This deviation has been explained theoretically by calculations performed at Argonne by T. Brage. A paper is in preparation.

iv. Lecture Series

A series of lectures was presented at Argonne on the following topics: "Hartree-Fock: Theory And Applications", "The MCHF Method", and "MCHF + Breit-Pauli".

b. Theoretical Atomic Physics (C. D. Lin*)

i. Theory of Anisotropy Transfer and Calculations of Alignment of np States Populated in Electron Capture by Highly Charged Ions

This study involves the analysis of the polarization of light emitted by excited atoms produced in ion-atom collisions or in electron-atom collisions. In this analysis, we need to account for the alignment of the excited states produced in the primary collision as well as the contribution due to the cascade from higher excited states. In other words, we need to consider the alignment transferred from the higher excited states. In performing the cascade analysis it is necessary to include the effect of spin-orbit interaction which tends to reduce the alignment. A general expression for alignment transfer has been derived and the method has been applied to the analysis of two sets of experimental data. A report on this work has been completed and is ready to be submitted for publication in Phys. Rev. A.

*Kansas State University, Manhattan, Kansas

ii. The Application of Hyperspherical Coordinates to Problems in Nuclear Physics (collaboration with Dr. T.-S. H. Lee, ANL, Physics Division)

The goal here is to use hyperspherical coordinates developed for atomic physics to nuclear few-body problems. By adopting phenomenological potentials between quarks, we want to calculate the mass spectra of hadrons and their properties. An initial test of the method has been very encouraging. We are able to confirm the known low-mass spectra of the nucleon and delta particle families. After further tests, the method will be applied to strange particles consisting of heavy quarks to make new predictions. It is also expected that the method can be extended to three-nucleon problems. Collaboration on this project will be continued in the future through short-term visits.

iii. Lectures in Atomic Physics

A series of seminars was presented at Argonne on the following topics: i) The Study of Coulombic Three-body problems in Hyperspherical Coordinates; ii) Theoretical Studies of Heavy Ion-atom Collisions; and iii) Spectroscopy and Collisions with Highly charged ions.

c. **Calculations in Theoretical Atomic Physics** (C. Bottcher*)

i. Analysis of "Coulomb Explosion" Results

A formalization has been developed for the analysis of data acquired in "Coulomb Explosion" experiments performed at Argonne by E. P. Kanter, Z. Vager et al. The method uses the concept of geometric invariants. As a longer range goal, we are setting up a TDHF calculation of simple collisionally induced Coulomb explosions such as $H_2^+ + He \rightarrow H^+ + H^+ + e + He^*$.

*Oak Ridge National Laboratory, Oak Ridge, Tennessee

ii. Radiative Electron Capture into Polarized States (collaboration with R. W. Dunford)

We are calculating the radiative electron capture properties for relativistic ions undergoing channelling in a polarized target. It is hoped that these calculations will lead to experiments where a signature for target polarization would be sought through studies of the associated x-rays.

iii. Theoretical Atomic Physics Seminars

A series of seminars on various aspects of calculational atomic physics has been presented. In addition, a 2-day workshop on "The Use of Supercomputers in Atomic Molecular and Optical Physics" is being organized and held at Argonne in March 1987.

d. Adiabatic Theorem for Atoms in Periodic Fields (M. Peshkin and D. Richards*)

Consider an atom in a periodic external field, possibly an rf electric field, in a practical case. The Hamiltonian for this system has the form $H(t) = H_0 + \gamma(t)\, H_1(t)$, where H_0 describes a finite number of relevant levels of the free atom, $H_1(t + T) = H_1(t)$, and $\gamma(t)$ is the slowly-varying amplitude of the external field. Let $\gamma(t)$ increase slowly from zero to some finite value and then return slowly to zero. We find that in the limit of slowly-varying $\gamma(t)$, the final state of the atom is the same as it would have been in the absence of the external field, provided that no transition frequency of the free atom is an integral multiple of $(2\pi/T)$. This result appears to be more general than previous adiabatic theorems. A paper is being prepared for publication.

*Open University, Milton Keynes, United Kingdom.

X. ATOMIC PHYSICS AT ATLAS

Argonne's heavy-ion accelerator facility, ATLAS (Argonne Tandem-Linac Accelerator System), offers many exciting possibilities for the study of atomic physics and in recognition of this, an ATLAS beamline dedicated to atomic physics was completed in 1986.

Ion beams are available at ATLAS which span an energy range from a few keV to a few GeV, and a variety of masses and charge states. We also have the ability to produce slowly-moving beams of very highly-charged ions by means of the accel/decel technique. We feel that the opportunities offered by ATLAS should be made readily accessible to the nation's atomic physics community. To this end, in addition to conducting our own research programs at ATLAS, we want to be available to act as collaborators and/or liaison persons for non-ANL atomic physics users of ATLAS.

Work on the future upgrade of the ATLAS facility with a positive-ion injector has been underway since 1985. Ion beams from the upgraded ATLAS will offer even more opportunities for atomic physics (full mass range, higher maximum energies, higher beam currents, etc.). In addition, the ECR ion source which is being built as part of the upgrade, will provide very attractive possibilities for atomic physics research with slow, highly-charged ion beams.

The new atomic physics beamline at ATLAS was completed and ready for experiments in 1986. The beamline components are designed to provide two target areas: the first, midway along the beamline (where access into an adjoining laboratory space provides the possibility for a crossed laser-beam/fast ion-beam interaction geometry); and a second larger area at the end of the beamline. There is an atomic spectroscopy target chamber equipped with a 2.2-meter grazing-incidence spectrometer (a VUV spectrometer can also be made available here). A general-purpose chamber will follow the spectrometer target chamber, in front of a well-shielded beam dump. An existing McPherson hemispherical spectrometer is available for high-resolution electron spectroscopy. This device will be equipped with a position-sensitive channel-plate detector in its focal plane. Also a crystal x-ray spectrometer with a position-sensitive detector is being made available to us from a group at NBS headed by Dr. R. Deslattes.

Several atomic physics experiments were scheduled and/or run in the past year. Some of the highlights include:

a. **Doppler-free Auger Electron Spectroscopy from Ne-like and Na-like High-Z Atoms** (H. G. Berry, L. Curtis,* R. Haar,*, E. P. Kanter, R. Schectman,* and D. Schneider†)

We have begun a series of measurements to study the level structures of high-Z Ne-like and Na-like ions. In the first experiments beams of 220-MeV Ni^{17+} and Ni^{10+} were excited in ion-atom collisions with argon and helium gas targets. The resultant LMM Auger electrons were measured at 0 degrees with a tandem parallel-plate electrostatic spectrometer. Because of the high beam velocity, this technique leads to a large kinematic expansion of the projectile frame electron energy spectrum when measured in the laboratory. These first tests were extremely promising. One of the problems encountered with previous runs was that there was insufficient magnetic shielding. We therefore plan to use a special magnetically-shielded chamber in the next run of this experiment.

The purpose of these experiments is to test fundamental atomic structure theory and models regarding the dynamic excitation processes in highly-ionized multi-electron systems. Measurements of the level structure of highly-stripped heavy ions provide important tests of relativistic many-body problems. Comparisons with theory in many-body systems are most meaningful for ions with a nearly closed shell where the fewest number of configurations are needed to generate accurate relativistic wave functions. To date most of the work has been done, both experimentally and theoretically near the closed K-shell. Recently, however, the fluorine-like, neon-like, and sodium-like systems have received a great deal of attention in moderately-ionized ($Z < 42$) systems. There is a need for more experiments to extend these measurements and to study nonradiative decay processes as well. These measurements complement ongoing x-ray spectroscopic studies and yield information regarding branching ratios, etc. This work also complements the existing theoretical effort in the vicinity of the closed shell. Furthermore, these systems are of direct interest to those who deal with high-temperature plasmas, since closed-shell systems persist over a wide range of temperatures and densities.

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b. **Lamb Shifts and Fine Structures of n = 2 in Helium-like Ions**
(H. G. Berry, R. W. Dunford, A. E. Livingston* A. S. Zacarias,* and Younan Lu*)

Measurements are in progress to study the spectrum of highly-ionized nickel (Z = 28) in the wavelength range of 100 to 300 Å using beam-foil spectroscopy. In a recent run the ATLAS accelerator was used to produce a beam of 375-MeV Ni^{11+} which was incident on a 100-μg/cm^2 carbon foil in a target chamber on the atomic physics beamline. The fluorescence after the foil excitation was observed at 90° to the beam direction in a 2.2 m grazing incidence monochromator equipped with a channeltron detector. A typical spectrum observed is shown in Fig. X-1. The spectral lines correspond to electronic transitions in nickel ions with 2 to 5 electrons. The analysis of these spectra will be used to determine a precise wavelength of the 1s2s $^3P_1$ - 1s2p $^3P_2$ transition in helium-like Ni XXVII. This measurement will test quantum electrodynamics and relativistic quantum mechanics to a precision of about 0.3% of the Lamb shift in nickel.

*University of Notre Dame, South Bend, Indiana.

c. **Heavy-ion-induced Desorption of Molecules** (J. E. Hunt,* E. P. Kanter, R. W. Dunford, W. Kutschera, R. C. Pardo, and M. Salehpour*)

We have initiated at ATLAS a study of the phenomenon of ion-induced desorption of molecular ions of large organic molecules through use of pulses of monoenergetic heavy-ion beams in well-established charge states. Related studies have already been undertaken at tandem accelerators in Uppsala and Erlangen involving, however, either lower-mass heavy ions or, with one exception, lower incident charges. From these studies the desorption rate for relatively light molecules was found to be a function of the electronic stopping power [$-(dE/dx) \propto (q^2/v^2)$] where q is the charge state of the incident heavy ions and v is its velocity. Both linear and quadratic dependences on the stopping power have been observed depending on the molecular species that was desorbed as well as on its polarity. The quadratic dependence is suggestive of a higher-order process. The dependence on the charge of the incident ion indicates that the energy transfer leading to

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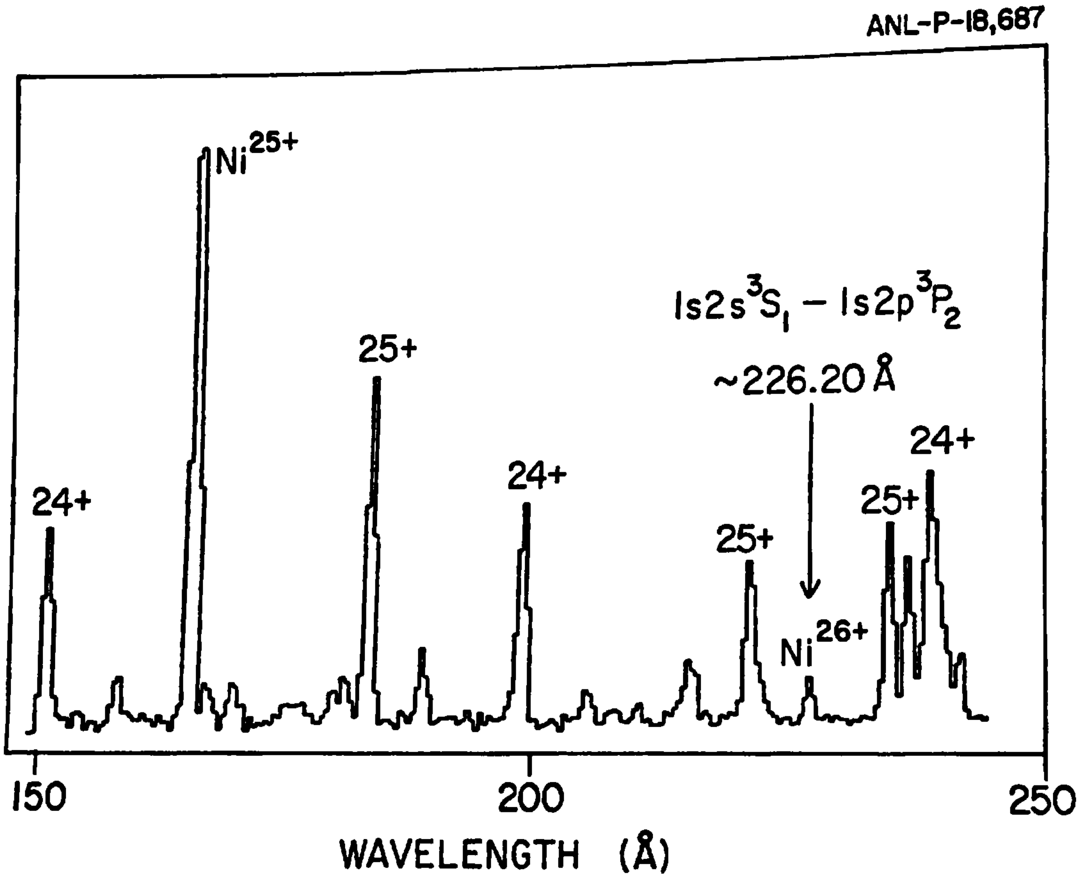

Fig. X-1. Beam-foil spectrum of 300-MeV nickel ions between 150 and 250 Å. The helium-like transition wavelength is close to the theoretical value of 226.28 Å.

desorption occurs in a thin atomic layer at the surface of the sample before charge equilibration has occurred. The charge q determines the "brightness" of the track, while v determines the interaction distance. For very massive molecules the increase of the desorption yield with the "brightness" appears to be much larger than for lighter molecules. Moreover, very interesting multiplicity distributions of fragment ions are found in coincidence with the desorbed heavy molecules. These throw light on the energy transfer in the desorption process. With ATLAS it is now possible to use much heavier ions as well as higher charge states than was possible up to now to study the desorption process systematically.

There is good reason to extend these measurements to ATLAS since there are strong indications that the probability for desorbing very massive molecular ions increases as one goes to high-energy high-Z projectiles.

In our first run at ATLAS, we used single pulses of ^{58}Ni ions accelerated to 300 MeV in the booster linac. We showed that we can in fact achieve single pulses $<$0.5 nsec in duration, with a repetition rate of 5.8 kHz, and that we can measure time-of-flight spectra for desorbed ions. Those tests used targets of Zn octylethyl porphine, polyethylene, glycol 400, polystyrene, and CsI. In two runs in the fall of 1986, a beam of 300-MeV $^{127}I^{40+}$ was used in target area II. This beam has a higher stopping power and a higher charge state which should result in higher yields of molecular ions. In these runs, a number of proteins in the mass range 25,000 - 50,000 were attempted, however equipment failures prevented us from obtaining good data. It is planned to pursue these experiments in future runs at ATLAS.

d. **Resonant Transfer and Excitation for Highly-charged Ions**
(K. H. Berkner,* E. M. Bernstein,† M. W. Clark,† W. G. Graham,‡, E. P. Kanter, and J. A. Tanis†)

The overall goal of this research is to probe fundamental atomic interactions in ion-atom collisions by correlating projectile charge-changing events with x-ray emission. Experimentally, this work is carried out by measuring coincidences between x rays (emitted from the projectile and/or target) and the outgoing projectile charge state of interest.

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†Western Michigan University, Kalamazoo, Michigan.
‡The New University of Ulster, Ulster, N. Ireland.

Resonant transfer and excitation (RTE) occurs when capture of a bound target electron is accompanied by simultaneous excitation of the projectile followed by de-excitation via photon emission. This process is analogous to dielectronic recombination (DR) in which the captured electron is initially free instead of bound. This process is of fundamental interest in plasma physics. RTE and DR proceed via an inverse Auger transition and, hence, are resonant for projectile velocities (in the rest frame of the electron) corresponding to the allowed Auger electron energies. For both RTE and DR many intermediate resonance states are possible, each one corresponding to an allowed Auger transition. Experimentally, observation of a resonant behavior in the x-ray yield associated with capture identifies the RTE mechanism. A formal theoretical treatment of simultaneous charge transfer and excitation in ion-atom collisions has been developed by Feagin, Briggs and Reeves. In our experiments at ATLAS, RTE was measured for Li-like Ni ions which is the heaviest system studied to date.

In the first run of this experiment at ATLAS we excited 550-MeV Ni^{25+} ions in a He gas cell and observed both K- and L-x-rays in coincidence with the charge-state-analyzed projectile ions. These experiments used a 2-dimensional position-sensitive low-pressure Breskin gas counter to detect the ions. Because of the high-count-rate capabilities of this detector we were able for the first time to study both the charge-changing and non-charge-changing components of the x-ray spectrum. This first run which took place in January 1986 was set up in the Large Scattering Chamber facility, while in a second run, which took place in October, the magnetic spectrograph in target Area III was used to analyze the charge states after capture. Additional runs of the experiment will be required in order to complete the RTE data for nickel.

STAFF MEMBERS OF THE PHYSICS DIVISION

Listed below are the permanent staff of the Physics Division for the year ending 31 March 1987. The program heading indicates only the individual's current primary activity.

EXPERIMENTAL NUCLEAR PHYSICS

Irshad Ahmad, Ph.D., University of California, 1966

*Jack Aron, B.S., Fenn College, 1955

Birger B. Back, Ph.D., University of Copenhagen, 1974

R. Russell Betts, Ph.D., University of Pennsylvania, 1972

†Lowell M. Bollinger, Ph.D., Cornell University, 1951

Cary N. Davids, Ph.D., California Institute of Technology, 1967

‡Melvin S. Freedman, Ph.D., University of Chicago, 1942

Stuart J. Freedman, Ph.D., University of California, 1972

Donald F. Geesaman, Ph.D., State University of New York, Stony Brook, 1976

§Bruce G. Glagola, Ph.D., University of Maryland, 1978

Michael Green, Ph.D., Indiana University, 1983

¶Walter F. Henning, Ph.D., Technical University, Munich, 1968

Roy J. Holt, Ph.D., Yale University, 1972

Harold E. Jackson, Jr., Ph.D., Cornell University, 1959

Robert V. F. Janssens, Ph.D., Université Catholique de Louvain, Belgium, 1978

Sheldon B. Kaufman, Ph.D., University of Chicago, 1953

Teng Lek Khoo, Ph.D., McMaster University, 1972

Dennis G. Kovar, Ph.D., Yale University, 1971

Walter Kutschera, Ph.D., University of Graz, Austria, 1965

*Alexander Langsdorf, Jr., Ph.D., Massachusetts Inst. of Technology, 1937

*Frank J. Lynch, B.S., University of Chicago, 1944

Thomas Moog, B.A., Princeton University, 1975

James Napolitano, Ph.D., Stanford University, 1982

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*Special Term Appointee.

†In charge of ATLAS operations and accelerator development.

‡Resident Associate Guest Appointee.

§ATLAS User Liaison Physicist.

¶Left the Physics Division in May 1986.

Richard C. Pardo, Ph.D., University of Texas, 1976

Karl Ernst Rehm, Ph.D., Technical University, Munich, 1973

*G. Roy Ringo, Ph.D., University of Chicago, 1940

Stephen J. Sanders, Ph.D., Yale University, 1977

†John P. Schiffer, Ph.D., Yale University, 1954

Kenneth W. Shepard, Ph.D., Stanford University, 1970

‡Silvia C. Tentindo Repond, Ph.D., University of Rome, 1979

*George E. Thomas, B.A., Illinois Wesleyan, 1943

Flemming Videbaek, Ph.D., University of Copenhagen, 1974

Lester C. Welch, Ph.D., University of Southern California, 1970

Bruce D. Wilkins, Ph.D., University of California, 1962

*Jan L. Yntema, Ph.D., Free University of Amsterdam, 1952

Benjamin Zeidman, Ph.D., Washington University, 1957

THEORETICAL NUCLEAR PHYSICS

§Arnold R. Bodmer, Ph.D., Manchester University, 1953

Richard R. Chasman, Ph.D., University of California 1959

Fritz Coester, Ph.D., University of Zurich, 1944

Henning Esbensen, Ph.D., University of Aarhus, 1977

§Dieter Kurath, Ph.D., University of Chicago, 1951

Stephen Landowne, Ph.D., Carnegie-Mellon University, 1970

Tsung-Shung Harry Lee, Ph.D., University of Pittsburgh, 1973

§James E. Monahan, Ph.D., St. Louis University, 1951

¶Vijay Pandharipande, Ph.D., University of Bombay, 1969

Murray Peshkin, Ph.D., Cornell University, 1951

Steven C. Pieper, Ph.D., University of Illinois, 1970

Robert B. Wiringa, Ph.D, University of Illinois, 1978

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*Special Term Appointee.

†Associate Director of the Physics Division. Joint appointment with the University of Chicago.

‡Joined the Physics Divison in February 1987. Term appointment to January 1988.

§Resident Associate Guest Appointee.

¶Special Term Appointee from University of Illinois, Urbana, Illinois.

ATOMIC AND MOLECULAR PHYSICS

H. Gordon Berry, Ph.D., University of Wisconsin, 1967

*R. Stephen Berry, Ph.D., Harvard University, 1956

William J. Childs, Ph.D., University of Michigan, 1956

†Robert W. Dunford, Ph.D., University of Michigan, 1978

‡Donald S. Gemmell, Ph.D., Australian National University, 1960

§Leonard S. Goodman, Ph.D., University of Chicago, 1952

Elliot P. Kanter, Ph.D., Rutgers University, 1977

¶Gilbert J. Perlow, Ph.D., University of Chicago, 1940

||Leslie Tack, Ph.D., University of Arizona, 1982

**Zeev Vager, Ph.D. Weizmann Institute of Science, 1962

Linda Young, Ph.D., University of California, Berkeley, 1981

ADMINISTRATIVE STAFF

††Allan Bernstein, M.B.A., Rosary College, 1986

‡‡Richard E. Combs, M.B.A., Lewis University, 1981

§§James R. Specht, A.A.S., DeVry Technical Institute, 1964

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*Joint appointment with the University of Chicago, Chicago, Illinois.

†Joined the Physics Division in September 1986.

‡Director of the Physics Division.

§Retired April 1986. Special Term Appointee.

¶Resident Associate Guest Appointee.

||Joined the Physics Division in September 1986. Term appointment to September 1988.

**Joint appointment with Weizmann Institute of Science, Rehovot, Israel.

††Executive Assistant. Joined the Physics Division in April 1987.

‡‡Assistant Director of the Physics Division. Left the Physics Division in March 1987.

§§Assistant Director of the Physics Division.

TEMPORARY APPOINTMENTS

Postdoctoral Appointees

Christian Beck (from Centre National de la Recherche Scientifique, France):
Nuclear physics research at ATLAS.
(July 1985--)

Georg H. Both (from University of Cologne, Germany)
Accelerator-based atomic physics.
(September 1985--December 1986)

Chia-Rong Chen (from University of Iowa Iowa City, Iowa):
Nuclear theory studies.
(September 1986--)

Bronislaw K. Dichter (from Yale University, New Haven, Connecticut):
Experimental heavy-ion research.
(October 1985--)

Lars Engström (from University of Lund, Sweden):
Accelerator-based atomic physics.
(September 1984--July 1986)

Ronald Gilman (from University of Pennsylvania, Philadelphia Pennsylvania):
Medium-energy pion and electron experiments.
(August 1986--)

Romain Holzmann (from University of Louvain, Belgium)
Gamma-ray spectroscopy of high-spin states at ATLAS.
(September 1984--)

John A. Johnstone (from Los Alamos National Laboratory, New Mexico):
Cloudy-bag model.
(November 1984--October 1986)

Jorg G. Keller (from the University of Darmstadt, W. Germany)
Nuclear physics at ATLAS.
(October 1985--)

Wen Chao Ma (from Vanderbilt University, Nashville, Tennessee):
Heavy ion nuclear physics research at ATLAS
(January 1986--)

Charles Price (from Indiana University, Bloomington, Indiana):
Heavy-ion transfer reactions.
(October 1986--)

Amarjit Sen (from the University of Western Ontario, Canada):
Laser-ion beam studies.
(June 1985--)

Michael Vineyard (Florida State University, Tallahassee, Florida)
Experimental nuclear physics using heavy ions.
(January 1984--June 1986)

Tzu-Fang Wang (Yale University, New Haven, Connecticut):
Heavy ion research at ATLAS.
(February 1986--)

Long-Term Visitors (at Argonne more than 4 months)

Christopher Bottcher (Oak Ridge National Laboratory, Oak Ridge, Tennessee):
Atomic theory.
(October 1986--)

*Mark Drigert (University of Notre Dame, Notre Dame, Indiana): Heavy-ion nuclear physics research at ATLAS.
(June 1986--)

Aurel Faibis (from Weizmann Institute of Science, Rehovoth, Israel):
Study of molecular ions and ion-beam target collisions
(January 1987--)

Charlotte Froese-Fischer (Vanderbilt University, Nashville, Tennessee):
Studies of properties of atomic states.
(January--June 1986)

Wolfgang Kühn (University of Giessen, W. Germany):
Heavy-ion nuclear physics research at ATLAS.
(July--December 1986)

Chii-Dong Lin (Kansas State University, Manhattan, Kansas):
Atomic theory.
(September 1986--January 1987)

†Harry J. Lipkin (Weizmann Institute of Science, Rehovot, Israel):
Investigation of current problems in hadron spectroscopy.
(July 1985--October 1986)

Zhenhao Liu (Beijung University, Beijing, Peoples Republic of China)
Heavy-ion research at ATLAS.
(April 1985--May 1986)

Eisuke Minehara (Japan Atomic Energy Research Institute, Tokyo, Japan):
Linac development.
(February 1985--September 1986)

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*Postdoctoral Appointee at Notre Dame University but resident at Argonne.

†1985-86 Argonne Fellow.

William R. Phillips (University of Manchester, England). Heavy-ion research at ATLAS. (October 1985--September 1986)

Ralph E. Segel (Northwestern University, Evanston, Illinois): Pion absorption studies. (August 1986--)

Yun-Yan Zhou (Institute of Modern Physics, Academia Sinica, Lanzhou, People's Republic of China): DAPHNE data-acquisition system. (September 1985--October 1986)

Resident Graduate Students

David T. Baran (Northwestern University, Evanston, Illinois): Medium-energy nuclear physics studies. (June 1985--)

Jordan B. Camp (University of Chicago, Chicago, Illinois): Weak interactions. (October 1982--October 1986)

Timothy Dinneen (University of Chicago, Chicago, Illinois): Laser spectroscopy of fast ions. (November 1986--)

Christopher Fasano (University of Chicago, Chicago, Illinois): Quark effects in nuclei. (October 1985--)

Michael A. Kroupa (University of Chicago, Chicago, Illinois): Search for magnetic monopoles using a plastic scintillator array. (July 1982--)

Frank L. H. Wolfs (University of Chicago, Chicago, Illinois): Research in heavy-ion physics. (September 1983--)

Short-Term Visitors (at Argonne less than 4 months)

A. Faculty

Paul Barker (University of Auckland, New Zealand): Weak interactions physics. (September-October 1986, February 1987--)

Patrick J. Cooney (Millersville State College, Millersville, Pennsylvania): Studies of the interaction of fast-moving ions with matter. (July--August 1986)

Carlos Dasso (Niels Bohr Institute, Copenhagen, Denmark): Heavy-ion reaction theory. (March-April 1986)

Hans Emling (GSI, Darmstadt, W. Germany): Nuclear structure studies. (November 1985--May 1986)

Peter Engar (Kansas State University, Manhattan, Kansas): Transfer of ATLAS technology. (April 1986)

Tom J. Gray (Kansas State University, Manhattan, Kansas): Transfer of ATLAS technology. (April 1986 and January 1987)

Edward L. Hohman (York Community High School, Elmhurst, Illinois): Summer high-school student coordinator. (June--August 1986)

Kevin Karnes (Kansas State University, Manhattan, Kansas): Transfer of ATLAS technology. (January 1987)

Bradley Kiester (Carnegie-Mellon University, Pittsburgh, Pennsylvania) Nuclear theory studies. (July-August 1986)

Eckehard Klemt (University of Heidelberg, W. Germany): Weak interactions physics. (July-August 1986)

Charles F. Maguire (Vanderbilt University, Nashville, Tennessee) Nuclear research at ATLAS. (June--August 1986)

Vincent Needham (Kansas State University, Manhattan, Kansas): Transfer of ATLAS technology. (April 1986)

Blaine Norum (University of Virginia, Charlottesville, Virginia): Polarized-target development. (July-August 1986)

Giovanni Pollarolo (University of Torino, Italy): Nuclear theory studies. (March-April 1986)

Francis Prosser (University of Kansas, Lawrence, Kansas): Heavy-ion studies at ATLAS (June-July 1986)

Yvonne Richter (Benet Academy, Lisle, Illinois): ATLAS development work. (June-August 1986)

B. Graduate Students

Tomas E. A. Brage (University of Lund, Sweden): Hyperfine interactions. (January--June 1986)

Robin Stern (University of Michigan, Ann Arbor, Michigan): Development work on University of Michigan super solenoid for detection of heavy-ion fragments (August-September 1986)

Daniel Zajfman (Technion, Israel): Interactions of fast molecular ions with matter. (March-July 1986)

Undergraduate Students

Bryan Affolter (DeVry Institute of Technology, Lombard, Illinois):
(February 1987 --)

James E. Angelo (University of Wisconsin, Madison Wisconsin)
(June-August 1986)

Michael Batek (University of Illinois, Urbana, Illinois):
(June-August 1986)

Daniel Bechtlofft (Aurora University, Aurora, Illinois):
March 1987 --)

Robert Bleicher (North-Central College, Naperville, Illinois):
(March 1987 --)

Daniel Boyer (Illinois State University, Normal, Illinois):
(January--April 1986)

James Brown (Kalamazoo College, Kalamazoo, Michigan):
(September-December 1986)

Laura Budrik (Illinois Benedictine College, Lisle, Illinois)
(March 1987 --)

Daniel Burns (Lewis University, Lockport, Illinois):
(March 1987 --)

Stephen Caracci (University of Illinois, Urbana, Illinois.):
(June-August 1986, December 1986-January 1987)

Lisa Chan (University of Chicago, Chicago, Illinois.):
(June-August 1986)

Daniel J. Ciarlette (Lewis University, Lockport, Illinois):
(October 1985--)

Thomas Coleman (College of St. Francis, Joliet, Illinois):
(September 1985--)

Vitaly Fiks (Wesleyan University, Middletown, Connecticut):
(June-August 1986)

Jeffrey M. Grandy (Rensselaer Polytechnic Institute, Troy, New York):
June-August 1986)

Kristen Harmon (Carleton College, Northfield, Minnesota):
(June-August 1986)

Thomas Jakubowski (University of Wisconsin Madison Wisconsin):
(June-August 1986)

Terence R. Jones (Institue of Technology, Ryswyk, The Netherlands):
(January 1987 --)

Michael Karls (St. Mary's College, Winona, Minnesota):
(March-August 1986)

Timothy McCormick (DeVry Institute of Technology, Lombard Illinois):
(March 1987 --)

Margaret McParland (Illinois Institute of Technology, Chicago, Illinois):
(November 1985--)

Sandra Monhardt (Lewis University, Lockport, Illinois):
(January 1986--)

Michael O'Keefe (Lewis University, Lockport, Illinois):
(November 1984--May 1986)

Stacey Otterson (University of Wisconsin, Stout, Wisconsin):
(September-December 1986)

Gregory Perschbacher (College of St. Francis, Joliet Illinois):
(February 1987 --)

Bonnie Pewitt (University of Kentucky, Lexington, Kentucky):
(May--August 1986)

Paul Reimer (Bethel College, North Newton, Kansas)
(January 1986--May 1986)

Paul Runkle (University of Wisconsin, Madison, Wisconsin):
(June-August 1986)

Eric Sather (University of Chicago, Chicago, Illinois):
(June--September 1986)

Brian Silverstein (University of Illinois, Urbana, Illinois):
(June-August 1986)

Lawrence Travis (Rutgers University, New Brunswick, New Jersey):
(June-August 1986)

Kenneth Venzant (University of Illinois, Chicago, Illinois):
(September-December 1986)

Daryl White (Walla Walla College, Walla Walla, Washington):
(June-August 1986)

Kristel Wickham (University of Oklahoma, Norman, Oklahoma):
(June-August 1986)

Stefan Zemsch (Technische Universität München, W. Germany):
(January 1987--)

TECHNICAL AND ENGINEERING STAFF

*Eric L. Bakke
Ralph Benaroya
Peter J. Billquist
John M. Bogaty
†Patric K. Den Hartog
‡William F. Evans
Joseph Falout
Jack T. Goral
Ray E. Harden
Dale J. Henderson
Donald V. Hulet
James M. Joswick
Raymond B. Kickert
Gary W. Klimczak
Robert Kowalczyk
Charles A. Kurtz
Paul Markovich
Floyd H. Munson, Jr.
Bruce G. Nardi
James E. Nelson
§Walter Ray, Jr.
¶Bruce J. Zabransky
Gary P. Zinkann

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*Joined the Physics Division in September 1986 for a period of one year.

†Supervisor of tandem-superconducting linac operations.

‡Left the Physics Division in February 1987.

§Left the Physics Division in October 1986.

¶In charge of Dynamitron accelerator operations.

PUBLICATIONS FROM 1 APRIL 1986 THROUGH 31 MARCH 1987

This list of "journal articles and book chapters," is classified by topic; the arrangement is approximately that followed in the Table of Contents of this Annual Review. The "reports at meetings" include abstracts, summaries, and full texts in volumes of proceedings; they are listed chronologically.

JOURNAL ARTICLES AND BOOK CHAPTERS

MEDIUM-ENERGY

BETA-DECAY ASYMMETRY OF THE NEUTRON AND g_A/g_V
P. Bopp, D. Dubbers, L. Hornig, E. Klemt, J. Last, H. Schutze, S. J. Freedman, and O. Scharpf
Phys. Rev. Lett. 56, 919 (1986)

PION ABSORPTION IN NUCLEI
Daniel Ashery and John P. Schiffer
Ann. Rev. Nucl. Part. Sci. 36, 207 (1986)

$^3He(\vec{p},\pi^+)^4He$ REACTION NEAR THRESHOLD
J. J. Kehayias, R. D. Bent, M. C. Green, M. A. Pickar and R. E. Pollock
Phys. Rev. C 33, 725 (1986)

STUDIES OF THE $^{18}O(\vec{p},\pi^-)^{19}Ne$ AND $^{26}Mg(\vec{p},\pi^-)^{27}Si$ REACTIONS AT T_p = 201 MeV
J. J. Kehayias, R. D. Bent, M. C. Green, M. Hugi, H.Nann and T. E. Ward
Phys. Rev. C 33 1388 (1986)

OBSERVATION OF THE $^{12}C(^3He,\pi^+)^{15}N$ REACTION NEAR THRESHOLD USING RECOIL DETECTION
W. Schott, W. Wagner, P. Kienle, R. Pollock, R. Bent, M. Fatyga, J. Kehayis, M. Green, and K. Rehm
Phys. Rev. C 34, 1406 (1986)

HEAVY-ION

OBSERVATION OF THE PROTON-PAIRING VIBRATION IN ^{48}Ca
F. Videbaek, Ole Hansen, M. J. Levine, C. Ellegaard, S. D. Hoath and J. M. Nelson
Nucl. Phys. A451, 131 (1986)

EMISSION PROBABILITIES OF γ RAYS ASSOCIATED WITH THE DECAY OF ^{229}Th AND ITS DAUGHTERS
R. G. Helmer, C. W. Reich, M. A. Lee and I. Ahmad
Appl. Radiat. Isot. 37(2), 139 (1986)

E1 TRANSITION PROBABILITIES WITHIN THE $K^\pi = 1/2^\pm$ PARITY-DOUBLET BANDS IN ^{225}Ra
C. W. Reich, I. Ahmad and G. A. Leander
Phys. Lett. 169B, 148 (1986)

POSSIBILITY OF OBSERVING A CONDENSED CRYSTALLINE STATE IN LASER-COOLED BEAMS OF ATOMIC IONS
J. P. Schiffer and O. Poulsen
Europhys. Lett. 1, 55 (1986)

QUASIELASTIC PROCESSES IN THE $^{28}Si + {}^{40}Ca$ REACTION AT 225 MeV
M. F. Vineyard, D. G. Kovar, G. S. F. Stephans, K. E. Rehm, G. Rosner, H. Ikezoe, J. J. Kolata and R. Vojtech
Phys. Rev. C 33, 1325 (1986)

UNEXPECTED ENTRANCE-CHANNEL EFFECTS IN THE DECAY OF THE COMPOUND NUCLEUS ^{156}Er
A. Ruckelshausen, R. D. Fischer, W. Kühn, V. Metag, R. Muhlhans R. Novotny, T. L. Khoo, R. V. Janssens, H. Groger, D. Habs, H. W. Heyng, R. Repnow, D. Schwalm, G. Duchene, R. M. Freeman, B. Haas, F. Haas, S. Hlavac and R. S. Simon
Phys. Rev. Lett. 56, 2356 (1986)

ARGONNE NATIONAL LABORATORY
Lester Welch
Nuclear and Plasma Sciences Society News No. 3, 19 (1986)

STRUCTURE OF A ONE-COMPONENT PLASMA IN AN EXTERNAL FIELD: A MOLECULAR-DYNAMICS STUDY OF PARTICLE ARRANGEMENT IN A HEAVY-ION STORAGE RING
A. Rahman and J. P. Schiffer
Phys. Rev. Lett. 57 1133 (1986)

LEVEL STRUCTURE OF PROTON-RICH N = 83 NUCLEI ^{150}Ho AND ^{152}Tm
J. McNeill, R. Broda, Y H. Chung, P. J. Daly, Z. W. Grabowski, H. Helppi, M. Kortelahti, R.V.F. Janssens, T.-L. Khoo, R. d. Lawson, D. C. Radford and J. Blomqvist
Z. Phys. A - Atomic Nuclei 325, 27 (1986)

SEARCH FOR ^{34}Si IONS IN ^{241}Am DECAY
M. Paul, I. Ahmad, and W. Kutschera
Phys. Rev. C, Brief Reports 34, 1980 (1986)

FISSION-LIKE YIELDS IN $^{16}O + {}^{40,44}Ca$ REACTIONS
S. J. Sanders, R. R. Betts, I. Ahmad, K. T. Lesko, S. Saini, B. D. Wilkins, F. Videbaek, and B. K. Dichter
Phys. Rev. C 34, 1746 (1986)

TWO-DIMENSIONAL FIELD MAPPING AND FIELD CORRECTION FOR A HIGH-RESOLUTION MAGNET WITH ABERRATION COMPENSATION
E. Minehara, P. Billquist, P. Den Hartog and W. Kutschera
Nucl. Instrum. Methods A252, 101 (1986)

LIFETIME MEASUREMENTS IN ^{184}Pt AND THE SHAPE COEXISTENCE PICTURE
U. Garg, A. Chaudhury, M. W. Drigert, E. G. Funk, J. W. Mihelich, D. C. Radford, H. Helppi, R. Holzmann, R. V. F. Janssens, T. L. Khoo, A. M. Vandenberg, and J. L. Wood
Phys. Lett. B 180, 319 (1986)

EVAPORATION RESIDUE CROSS SECTIONS AND AVERAGE NEUTRON MULTIPLICITIES IN THE $^{64}Ni + ^{92}Zr$ AND $^{12}C + ^{144}Sm$ REACTIONS LEADING TO ^{156}Er
R. V. J. Janssens, R. Holzmann, W. Henning, T. L. Khoo, K. T. Lesko, G. S. F. Stephans, D. C. Radford, A. M. Vandenberg, W. Kühn, and R. M. Ronningen
Phys. Lett. B 181, 16 (1986)

NUCLEAR PROPERTIES OF ACTINIDE NUCLIDES
Irshad Ahmad and Paul R. Fields
The Chemistry of the Actinide Elements, Second Edition, Volume 2, ed. Joseph J. Katz, Glenn T. Seaborg, Lester R. Morss (Chapman and Hall--London, New York 1986) pp. 1649-1674

OCTUPOLE DEFORMATION IN NEUTRON-RICH BARIUM ISOTOPES
W. R. Phillips, I. Ahmad H. Emling, R. Holzmann, R. V. F. Janssens, and T.-L. Khoo
Phys. Rev. Lett. 57, 3257 (1986)

FISSION FOLLOWING FUSION OF Ni + Sn
K. T. Lesko, W. Henning, K. E. Rehm, G. Rosner, J. P. Schiffer, G. S. F. Stephans, and B. Zeidman
Phys. Rev. C 34, 2155 (1986)

CHARACTERISTIC TIME FOR MASS ASYMMETRY RELAXATION IN QUASI-FISSION REACTIONS
W. Q. Shen, J. Albinski, R. Bock, A. Gobbi, S. Gralla, K. D. Hildenbrand, N. Herrmann, J. Kuzminski, W. F. J. Müller, H. Stelzer, J. Töke, B. B. Back, S. Bjørnholm, S. P. Sørensen, A. Olmi, and G. Guarino
Europhys. Lett. 1, 113 (1986)

NONEQUILIBRIUM POPULATION OF MAGNETIC SUBSTATES AND EXCITATION-ENERGY DIVISION IN THE DECAY OF AN ORBITING COMPLEX
A. Ray, D. D. Leach, R. Vandenbosch, K. T. Lesko, and D. Shapira
Phys. Rev. Lett. 57, 815 (1986)

PROJECTILELIKE FRAGMENTS FROM ^{14}N BEAMS AT 15, 25, AND 35 MeV/NUCLEON
G. S. F. Stephans, R. V. F. Janssens, D. G. Kovar, and B. D. Wilkins
Phys. Rev. C 35, 614 (1987)

THEORY

BINDING ENERGIES OF HYPERNUCLEI AND Λ-NUCLEAR INTERACTIONS
A. R. Bodmer and Q. N. Usmani
Nucl. Phys. A450, 257 (1986)

IMPLICATIONS OF DIRAC NUCLEON DYNAMICS FOR THE BINDING OF LIGHT NUCLEI
B. D. Keister and R. B. Wiringa
Phys. Lett. B173, 5 (1986)

EFFECT OF $\pi\pi$ INTERACTIONS IN πN SCATTERING
John A. Johnstone and T.-S. H. Lee
Phys. Rev. C. 34, 243 (1986)

CONTINUUM POLARIZATION TRANSFER IN 500-MeV PROTON SCATTERING AND PIONIC COLLECTIVITY IN NUCLEI
L. B. Rees, J. M. Moss, T. A. Carey, K. W. Jones, J. B. McClelland, N. Tanaka, A. D. Bacher and H. Esbensen
Phys. Rev C 34, 627 (1986)

INCIPIENT OCTUPOLE AND 2^6-POLE DEFORMATION IN THE MASS REGION $220 < A < 230$
R. R. Chasman
Phys. Lett. B. 175, 254 (1986)

DYNAMICAL SOURCE OF MASS SPLITTING IN AN SU(3) BAG MODEL
John A. Johnstone
Phys. Rev. D 34, 1499 (1986)

EVIDENCE FOR THE ENERGY DEPENDENCE OF EFFECTIVE HEAVY-ION INTERACTIONS
S. Landowne, C. H. Dasso, and G. Pollarolo
Phys. Lett. B 178, 336 (1986)

MAGNETIC MONOPOLES, ELECTRIC CURRENTS, AND DIRAC STRINGS
Harry J. Lipkin and Murray Peshkin
Phys. Lett. B 179, 109 (1986)

QUASIELASTIC PROTON-NUCLEUS SCATTERING AT 300-800 MeV
H. Esbensen and G. F. Bertsch
Phys. Rev. C 34, 1419 (1986)

COMMENT ON "ANOMALOUSLY BROAD SPIN DISTRIBUTIONS IN SUB-BARRIER FUSION REACTIONS"
C. H. Dasso, H. Esbensen, and S Landowne
Phys. Rev. Lett. 57, 1498 (1986)

UNITARY MESON-EXCHANGE CALCULATION OF $NN \rightarrow NN\pi$ REACTION
A. Matsuyama and T.-S. H. Lee
Phys. Rev. C 34, 1900 (1986)

ON THE AHARONOV-BOHM SCATTERING
J. Q. Liang
Il Nuovo Cimento 92, 167 (1986)

EFFECTS ON SPIN ASYMMETRIES OF SPECIAL EFFECTS AT 90°
Harry J. Lipkin
Phys. Lett. B, 181, 164 (1986)

TRIAXIALITY AND REFLECTION ASYMMETRY IN THE MASS REGION $A \sim 220$
R. R. Chasman and I. Ahmad
Phys. Lett. B182, 261 (1986)

ON THE NUCLEAR POLARIZATION POTENTIAL FOR HEAVY-ION SCATTERING
C. H. Dasso, S. Landowne, G. Pollarolo and A. Winther
Nucl. Phys. A459 134 (1986)

PHOTO AND ELECTROPRODUCTION OF Δ AS TEST OF DELTAS IN NUCLEI
H. J. Lipkin and T.-S. H. Lee
Phys. Lett. B183, 22 (1987)

VARIATIONAL MONTE CARLO CALCULATIONS OF GROUND STATES OF LIQUID ^4He AND ^3He DROPS
V. R. Pandharipande, Steven C. Pieper and R. B. Wiringa
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FINITE RANGE EFFECTS IN MULTI-DIMENTIONAL BARRIER PENETRATION PROBLEMS
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